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Physics in the Production and Use of Bulk Crops*

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I

WHEN the science of physics is mentioned, most people think right away of Einstein, or of relativity and the quantum theory. You are therefore probably wondering why I, a physicist, should be here. What, you have every right to ask, has physics got to do with the chemurgic program? What part does physics play either in the production of crops or in the use of those crops as the raw products of industry? Well, before I ever agreed to speak, I made very sure that there was an ample and convincing answer. I found, in fact, that the subject of physics in the chemurgic program is too big for me or for any one man to cover completely. I can speak here about only a few ways that physics enters in. I will first talk about physics in the *utilization* of farm and forest products.

Physics is the branch of general science which covers those things found in nature which we call mechanics, heat, light, sound, electricity and magnetism. The elemental tools of the physicist are the measuring rod, the weighing balance and the clock or stopwatch. Derived from these he has other devices such as the thermometer, the speedometer, the pressure gauge, all electrical instruments and the compass needle. He studies nature with these devices and applies educated common sense to what he learns. I don't want to make any mystery about physics. Relativity and the quantum theory are important parts of physics it is true but they are merely mathematical ways of looking at things which have a practical, simple, everyday aspect also. Every good chemist and every good engineer has an excellent working knowledge of physics and uses it everyday in his work. It is through chemists and engineers as much as any way that physics contributes to the chemurgic program.

Henry A. Barton

Engineers build the railways and trains, the highways and trucks which take agricultural products to the factories. They also build the factories themselves and all the machinery in the factories. To do such things, engineers use their knowledge of structural forces and of the laws

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of motion. In that way, they know how heavy to make steel I-beams, how to lay re-enforcement in concrete, how much to bank railway curves and how to oil a bearing. I could go on listing the physical things engineers know very much longer than my voice would last. If they had not learned these things engineers could not have done so much to develop this modern world, our present day civilization in which the farmer's market is now no longer limited to food and no longer restricted to his own immediate neighborhood.

The *chemist* has gained general recognition more recently than the engineer but he is already very important to the farmer. The chemists know and use physics and, here again, the list of ways is so long that you would not want to listen to them all. When the chemist applies heat with his Bunsen burner, when he measures temperature with his thermometer, when he distils, when he stirs, when he weighs, when he makes almost any measurement at all, he is for the moment a practising physicist.

The point I am making is that physics is a very fundamental science that runs through all the other sciences and, indeed, through all of our daily life. Wherever you find engineering or chemistry, you find physics. This is one way of showing how physics comes into the chemurgic program in every last detail of it.

II

Now, I want to approach the subject from a different and more specific angle. Let me take a specific industry as an example, namely, the paper industry. As you all know, this industry uses wood and other cellulose crops as its raw material. The essential thing about these raw materials is that they are made of very strong fibers. Nature makes them that way so that trees and plants can stand up from the ground and compete with other plants to get the air and sunlight necessary for their chemical life.

The paper industry takes these fibrous materials and breaks them up mechanically and chemically into clean individual fibers. These are then put through a machine called a beater whose functioning is not very well understood but it seems to press and form the fibers in such manner that they will fit together better in the finished paper. In these preliminary processes, hydraulics plays a principal part. Hydraulics is a branch of physics. The fibers are suspended in water. In some stages this fiber and water mixture is thicker than soup, in others, much thinner than milk. Physical laws control the flow of these liquids, physical methods measure and control their thickness, it is due to physical forces that the tiny fibers do not all settle to the bottom nor float to the top. A man must know some physics to understand what happens, and he uses physics to make it happen the way he wants it to.

Finally, a thin mixture of cleaned, cut, pressed and sized fibers and water diluted down perhaps to only 2 or 3 percent wood to 97 or 98 percent water is fed into the paper machine. All this water has been used to carry and to hold the fibers while they were cut and pressed and otherwise prepared. It sounds a little like using the brook through the pasture for a chopping block. Some of us physicists wonder whether it's the best way to get the job done. We think extensive research with microscopes, other physical instruments and a pencil and a piece of paper would turn up better ways of handling and fitting cellulose fibers for the purpose of making paper.

As a matter of fact, the very first step in the papermaking machine (Fourdrinier) is to get rid of the water. This is done by shaking, draining, squeezing and evaporating. Evaporation, like the others, is a phenomenon covered by physics and it is well understood. Evaporation is the most ordinary form of drying. If a farmer ever stops sweating, his shirt begins to dry because the molecules in his liquid sweat jump out into the air and float away. You know they do because you can smell them in the air you breathe. The heat of his body makes them move faster and escape quicker. However, the air around him gets in their road sometimes. That is, a molecule of water jumping out is quite likely to hit a molecule which is part of the air and bounce back in again. His shirt would dry faster if the surrounding air was all removed. That would be a vacuum and it would be hard on the farmer. Paper, however, can stand a vacuum. It is interesting to speculate whether vacuum drying can be used

to any great extent in place of heat drying in a paper mill. Research alone can tell.

Research alone can tell whether it is necessary for fibers to be mixed with many times as much water only to be wrung out again; whether great and complicated machinery costing every mill many thousands of dollars is necessary simply to shape and arrange fibers in a thin, even formation; why it is that the best papers realize less than 15 percent of the natural strength of the cellulose fibers of which they are made.

III

I have referred at length to the paper industry because it is one where there are many applications of physics now and where there can be many more. Physicists now at work in the industry deal with control and specifications mostly. They rig up photoelectric cells to watch the concentration of fibers at the feeding end of the paper machine, automatic indicators and controllers of moisture content in the finished paper, and other devices to assure uniform quality of output. They inspect and specify paper for its color, its fiber formation, its strength, durability, smoothness and other characteristics such as how easily type will show through on the back and how much glare will be caused by reflected light.

Paper has infinite uses. It is good to wrap things with because it is so strong for its weight and bulk. The printed word is put on paper because it is the cheapest kind of material which can be made with a lot of surface per pound. This report of last year's conference contains 430 pages, approximately seven by ten inches in size. That's 209 sq. ft. of surface that you can lift with your little finger or put in your coat pocket.

The future of paper may be even greater than its past. If research can lower the manufacturing cost of paper and improve its quality, there is no limit to the market for it. Magazines and newspapers will be able to print more pages; books will be made of better paper and more books will be printed; paper as wrapping will compete more with other materials. Most of all, however, new uses for paper will develop. The manufacture of wall-boards and other plastics built up of layers of impregnated paper is already a large industry. Think what would happen if these materials could seriously compete in price with wood and other conventional materials used in building construction!

The paper industry is only one of many in which physics plays its double role: first, that of control and specification at the present time and, second, that of research for cheaper and better products in the future. The same line of argument runs through the plastics industry. Plastics are materials that are chemically and physically mixed, combined or dissolved and then molded by casting or pressing. Physical pressure and heat play a part in their manufacture; physical instruments at all stages guide and control. How plastic is a material? Does it give and snap back like rubber, does it squeeze out like toothpaste, does it take a set or can it be processed over again? Physical measurements give the answer.

IV

Looking ahead, physicists are seeking to improve the machinery and methods of the plastics industry, trying to design in accordance with better understanding of the natural laws of plastic flow. In the eyes of the physicist, the plastics industry is not as scientific as it should be. Too much depends on personal craftsmanship and on cut-and-try methods. Too much time is spent on making each piece and too many pieces are spoiled. The physicist would like to help make plastics manufacturing a science so machines would work faster and finished products would pass the inspector practically 100 percent.

Anything which raises quality and cheapens price by improved or simplified methods of manufacture is a gain for the farmer. His market is increased thereby and the price he gets is maintained or, more likely, bettered. Prices usually go up with demand. What can happen and actually is happening in the paper and plastics industries is happening in other industries as well. This is the essence of the whole chemurgic program.

I want to emphasize that one *certain* consequence of research or technological improvement is the expansion of the market for raw materials, in this case the bulk crops of the farm. I want to emphasize also the additional effect of increasing the farmer's portion of the price received for the finished article.

V

To take advantage of this larger and richer market the farmers of America will want to increase their output to keep pace with its development and here the science of physics comes in again. The physicist in his laboratory is now and will be more and more the strong ally of the farmer in his field. He will help the farmer to produce more per acre and to do it cheaper than he now can.

The yield per acre, of course, depends on the physical and chemical constitution of the soil, on the water content of the soil throughout the growing season, on the sunlight and the wind and weather. The yield from the same acre year after year depends on soil conservation through replacement of exhausted chemicals necessary for plant growth and through avoidance of wind and water erosion. All of these factors are being studied now by physicists.

In studying the physical constitution of the soil, the laboratory man asks what materials are mixed in it, how large are the particles, how uniformly are they mixed, how freely can the chemicals diffuse through the soil to plant roots, is the soil mass too loose or too caked for free growth, is rain water held too long or not long enough before it seeps down or runs off? He studies also the ways in which irrigation can be used, the methods of plowing which will retard erosion. He thinks about the slope of land in connection with the height of the sun. A field which lies well for winter wheat may not be so efficient for summer use or *vice versa*.

The physicist has quick and very sensitive ways of helping the chemist in soil analysis. Some soils have selenium, a chemical element like phosphorus, which is bad for crops or livestock grazing on them. The spectroscope can detect the faintest trace in a few minutes time. In other ways, the physicist and the soil chemist go hand in hand.

Passing on from the subject of soils, I could say a great deal about the forcing of crops, but I will not because forcing methods are generally expensive and mainly applicable to food crops instead of to the bulk crops grown for industrial use. I will just say that the physicist, with his knowledge of hot houses, radiation and electric effects is right at home with the forcing of crops. The next time you build a greenhouse, talk to a physicist first. He may save you as much as a third of the construction cost and give you a better greenhouse. The opportunity of improving conventional greenhouses has been amply demonstrated at the Boyce Thompson Institute for Plant Research, Inc., at Yonkers, N. Y.

VI

Over a period of good and bad years the average yield per acre depends, as every farmer knows, on the extent of crop loss. Crops may be lost (among other ways) through unfavorable weather conditions, plant diseases, insect pests and spoilage in storage. The science of physics can and does play a large part in the control of each one of these distinctive factors. I do not mean that the physicist can do anything about the weather itself. Like everyone else, he has to take it as it comes. But he knows better than most people how to do just that—how to make adjustments and compensations for the weather. Let me give a few examples. I have already mentioned methods of resisting erosion and making intelligent use of the lie of land in the sunlight. Another example is the use of flares to protect the fruit orchards in southern California against frost. It is not the heat of these flares which is important. About the only thing that's big enough to heat all outdoors is the sun itself. The trick is rather the smoke blanket they spread over the area. They keep the natural warmth of the ground from escaping by radiation out into the empty sky. This is a physicist's trick. He deals with radiation. Just as ordinary clouds keep the heat of the sun from reaching the earth in the daytime so artificial clouds keep the heat of the earth from escaping at night. Have you ever noticed how it is on the clear nights in the fall that the first sharp frosts come?

But the main thing the physicist can do about the weather is to predict it. All the successes and all the failures of the weather forecaster have to be taken on the heads of the physicists, for the science of meteorology is a branch of the science of physics. The weather is made of motion (that is, wind), of condensation (that is, fog, dew, rain, snow and hail), of evaporation (resulting

in clearing skies and drying ground) and of radiant energy (that is, the warm light of the sun). All of these things are the stock in trade of the professional physicist. He understands how they act. He knows how they are related to each other. He has barometers and humidity meters and wind meters which he watches and which he sends up in balloons. He maps the state of the atmosphere all over the world and tries to predict what's coming next in every county of every state of the union. This is valuable in many ways just as any warning is. The fruit grower knows when to get his smudges ready, the dairy farmer when to get his hay crop in. There is a fairly good hope that a little more research in meteorological physics will lead to reliable predictions by seasons rather than just by days. If this hope is realized and the agriculture of whole regions can be adjusted to anticipated droughts and wet spells, then the debt of the farmer to the physicist will be very great indeed.

Plant diseases are spread in many ways, just as animal and human diseases are. To diminish or prevent this spread, such things as seed disinfectants and sprays are used. Physics comes into the manufacture of these and into the methods of using them. It is a tremendous job to spray an orchard. I would like to see what could be done with dry powder of suitable grain size and the use of power fans. We know much more at this moment than we ever did before about air convection and about fans. Research might enable us to treat whole orchards at once not tree by tree. I am not referring to the dropping of powder from airplanes. I would only be interested in a method more practical, effective and economical than that.

VII

I do not believe enough research has been done in the disinfecting of seeds by ultraviolet light. The sun contains ultraviolet light, and sunlight is an enemy to many surface infections. A thorough study should be made of the idea of unrolling cheap sheet-metal reflectors on the ground to make sunlight hit the under surfaces of foliage and bark for suitable periods of time. Blights of certain kinds might be susceptible to some control by this means.

I advance these speculative ideas to show the need for more research by physicists on agricultural problems. They may be no good. It is very easy to think up a lot of devices and methods which might be of great value to the farmer. Whether they really are or not is what research alone will tell. Research is generally a good gamble. It seldom does any harm and often does a great deal of good.

Insect pests are controlled by sprays and other applications of chemicals. Insect traps are also used, and the method of traps has undergone some development in recent years. We have Japanese beetle traps all over the East, but they are not sufficient. Physicists are working with entomologists in the study of ways of attracting and destroying insects in something like adequate quantities. We have to catch bugs by the millions, not by the thousands. It might be more effective if all the money spent on bottle traps, chemicals and quarantines and on the salaries of quarantine officers, were spent instead on modern electrical traps, spaced not too far apart over whole regions of the country. As you may know, these traps contain bright lights which attract insects from large areas and they are surrounded by a cage of wires which electrocute the insects as they approach. An adequate tryout of this method is just the kind of large scale research that the government should conduct more vigorously on behalf of American agriculture.

All agricultural products are subject to spoilage after harvest. For example, they may rot or they may burn from spontaneous combustion. The loss may occur either before or after the farmer has completed his sale. In either case, it is a waste and the farmer suffers. Now the science of physics is the parent of air control. Storage barns and elevators need ventilation, the presence of moisture must be limited and temperatures must be kept from going too high. All of these things can be taken care of by proper design of storage space, proper walls and roofs, proper ventilating and handling machinery. It is one of the jobs of the physicist to provide these things as cheaply as possible—working, of course, with engineers.

I am reminded at this point that if I were talking about food products, I would say that refrigeration, quick freezing and vacuum canning are all applications of physics.

VIII

I have said but little in the field of biophysics. Biologists these days are not only bringing out varieties of existing plants which are bred to be high in starch or in sugar or in other desired respects, but with the help of the physicists' radium and x-rays, they are producing sports and new species some of which may be ideally suited as industrial raw materials. While I have talked about physics in the service of the engineer and the chemist, I have not mentioned its use by the botanist who studies the mechanism of plant growth. There is not time enough to go into details but, here again, the science of physics shows its fundamental nature.

So when you ask me where physics enters into the chemurgic program, my only possible answer is: Everywhere! It lies at the heart of it, it goes along as part of the other contributing sciences and its role does not end until the final process of manufacture has been completed. In fact, it is usually for physical reasons that a market exists for chemurgic products at all. Paper is wanted for its strength in proportion to bulk, plastics are wanted for their strength, durability, color and ease in shaping, oils are wanted because they soften or lubricate or flow pigments onto surfaces in paints and lacquers. All of these are physical reasons. Alcohol from farm products is wanted in automobile engines which, aside from the combustion in the cylinders, are entirely physical devices, their power and efficiency depending on physical laws.

I think you will agree even if you only accept a quarter of what I have said, that we should train more physicists to deal with chemurgic problems, get more physicists into government technical services and into agricultural colleges and devote more public and private funds to the support of physical research.

But here is another who took up the study of physics as soon as he came to college, and continued it all through his student days, and his career consists in controlling and directing physical phenomena by his knowledge of physical laws, or in designing machines which depend on physical principles. And what does he call himself, and what does the world call him? An electrical engineer or a radio engineer, a designer of lenses or a maker of turbines, a naval engineer or an acoustical engineer, a mechanical engineer or an aerodynamical engineer, and only the census tables could say what else! He has not departed from physics, but physics has lost the credit of his achievements. The colonies of our science have renounced the name of the mother country, and even the emigrant often has the notion that in settling in the fields of engineering he is changing his nationality, whereas actually he has never left the empire of physics. This empire is truly a very great one; and if it were known in its entirety by the name of physics, that name would assuredly be no unfamiliar word.

—Karl K. Darrow, *The Renaissance of Physics.*
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X-RAY DETERMINATION OF THE STRUCTURE OF LIQUIDS AND GLASS*

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Introduction

THE x-ray diffraction pattern of a liquid or a glass consists of one or more broad diffuse rings. It is distinctly different from the powder pattern of a typically crystalline material which shows a large number of fairly sharp rings. Only in recent years has a serious attempt been made to analyze the diffraction patterns of amorphous materials, such as liquids and glasses, and to determine their structure. Most of the early attempts to analyze the patterns approached the problem from the point of view of crystalline diffraction, and tried to explain the diffraction bands as Bragg reflections from layers of atoms such as the planar layers in crystalline structures. Only recently have x-ray workers realized that an x-ray scattering pattern showing maxima and minima can be produced solely by the existence of a few fairly definite interatomic distances in the sample material. For example, in a monatomic liquid, measuring from the center of any one atom we would never expect to find the center of another atom closer than a distance equal to the atomic diameter, but at roughly this distance we would expect to find several atoms. This fact alone is enough to predict a diffraction pattern showing maxima and minima.

In a crystal we have an arrangement of atoms in which some unit of structure repeats itself identically at regular intervals in three dimensions. The positions of all the atoms in a crystal can be expressed in terms of any arbitrary origin of coordinates. In a simple liquid the positions of the atoms would be completely indefinite with respect to a fixed origin of coordinates, but would show a short range type of structure if the origin were allowed to ride about on the center of any one atom.

Glass is usually called an under cooled liquid, the name suggesting that although it has many of the mechanical properties of a true solid it differs from the crystalline form of matter by not having passed through a sharp or definite transition in solidifying from the melt. From the x-ray studies we shall conclude that glass and liquids are similar in that both are amorphous forms of matter. In one respect, however, their structures differ; in a glass each atom has permanent neighbors at a fairly definite distance, while in a liquid the neighbors about any atom are continually changing.

While the x-ray pattern of a typically amorphous material is distinctly different from that of a typically crystalline material, there is no sharp division between them. For crystalline powder samples of smaller and smaller particle size, the powder pattern lines broaden continuously and for small enough crystalline particles the pattern becomes the so-called amorphous pattern similar to that of a liquid or a glass.

Experimental Methods

The x-ray diffraction pattern of a liquid or glass is usually made by allowing a finely collimated x-ray beam to fall upon the sample and recording the scattered radiation upon a cylindrical film surrounding the scattering material. In working with glasses the sample is usually a small rod 0.5–1.0 mm diameter. With liquids the

* Paper delivered at Symposium on the Solid State, Bryn Mawr College, June 16, 1937.

sample may be held in a thin walled container or a free stream of the liquid may be used. The radiation is generally Mo$K\alpha$(0.710A) or Cu$K\alpha$(1.539A). Because of the diffuseness of the x-ray patterns of liquids and glasses it is very diffcult to correct properly for background and extraneous scattering. It is therefore necessary to take precautions to eliminate all such effects. The radiation is made essentially monochromatic by reflecting from a rock salt crystal. Air scattering at small angles is eliminated by either evacuating the camera or filling with a light gas.

Interpretation of Diffraction Patterns

From a typical liquid or glass diffraction pattern, containing three or four diffuse rings, the only quantity which can be determined directly and uniquely is the radial distribution function. This is obtained from a Fourier analysis of the experimental x-ray scattering curve, and gives directly the average number of atoms to be found at any distance from a given atom. The method of Fourier analysis is equally applicable to a liquid, a glass, or a powdered crystalline material, so that in using this method, one is not making any *a priori* assumptions as to the structure of the material in question.

The theory of the method of Fourier analysis will be developed here for the simple case of a material containing only one kind of atom, for example, liquid sodium. A monochromatic x-ray beam falls upon an array of atoms, and the radiation scattered at an angle 2θ to the direction of the primary beam is observed at a point P. The amplitude of the unmodified scattered radiation is given in electron units (using the radiation scattered by a single electron according to classical theory as the unit)

$$E_p = \sum_n f_n \exp\left[\frac{2\pi i}{\lambda}(\bar{s}-\bar{s}_0)\cdot\bar{r}_n\right]. \qquad (1)$$

$\bar{s}$ and $\bar{s}_0$ are unit vectors giving the direction of the scattered and the primary radiation.

$\bar{r}_n$ is a vector giving the position of atom n.
f_n is the atomic scattering factor of atom n.

The manner in which one proceeds from Eq. (1) depends upon whether one is at liberty to assume the material to be crystalline. For a crystalline material the positions of all the atoms can be expressed in terms of one coordinate system. The summation of Eq. (1) can be carried out and an expression secured for the resultant amplitude and intensity. This intensity expression will show sharp maxima in the usual directions given by the Bragg law.

If one is not at liberty to assume the material to be crystalline, it is not possible to carry out the summation indicated in Eq. (1). Multiplying (1) by its conjugate complex quantity, and then averaging the resulting expression for intensity as the rigid array of atoms is allowed to take all possible orientations in space, one obtains the Debye equation.[1]

$$I = \sum_m \sum_n f_m f_n \frac{\sin sr_{mn}}{sr_{mn}}, \qquad (2)$$

$$s = \frac{4\pi \sin\theta}{\lambda},$$

r_{mn} = the distance from atom m to n.

In applying Eq. (2) to a liquid or glass it is obviously not necessary actually to rotate the sample, since any configurations which may exist will be found many times with all possible orien-

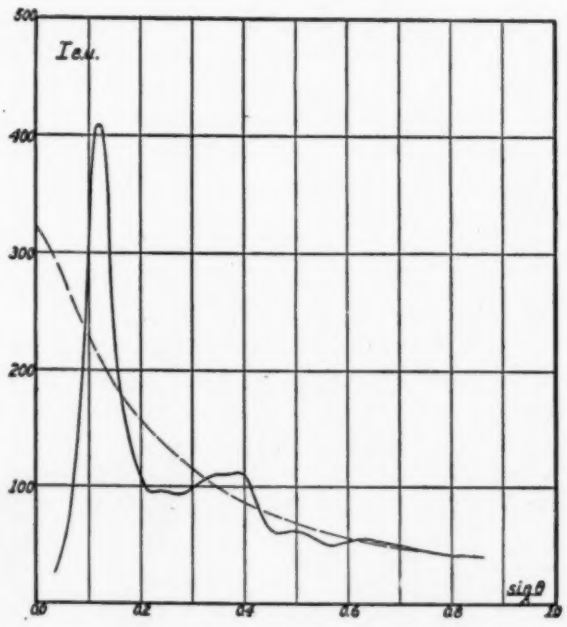

FIG. 1. X-ray intensity curve for vitreous SiO_2 in e.u. per SiO_2; dashed line, independent scattering per SiO_2.

tations. For a material consisting of only one kind of atom, and assuming that on the average each atom is surrounded in the same way as every other atom, (2) becomes

$$I = Nf^2 \sum_n \frac{\sin sr_n}{sr_n}, \qquad (3)$$

where N is the effective number of atoms in the sample.

Introducing a radial distribution function such that $4\pi r^2\rho(r)dr$ is the number of atoms between distances r and $r+dr$ from any atom, (3) becomes

$$I = Nf^2\left\{1+\int_0^\infty 4\pi r^2\rho(r)\frac{\sin sr}{sr}dr\right\}, \qquad (4)$$

$$s\left(\frac{I}{Nf^2}-1\right) = 4\pi\int_0^\infty r(\rho-\rho_0)\sin srdr$$

$$+4\pi\int_0^\infty r\rho_0 \sin srdr. \qquad (5)$$

Except for very small values of s the second integral is zero. Inverting the rest of the equation by the Fourier integral theorem we obtain finally

$$4\pi r^2\rho(r) = 4\pi r^2\rho_0 + \frac{2r}{\pi}\int_0^\infty si(s)\sin rsds, \qquad (6)$$

where $$i(s) = \left(\frac{I}{Nf^2}-1\right).$$

ρ_0 is the average density of the sample in atoms per unit volume.

The quantity $si(s)$ is obtained directly from the experimental scattering curve. The integration involved in Eq. (6) is then carried out for a number of different values of r. The resulting values of $4\pi r^2\rho(r)$ plotted against r give the radial distribution of atoms about any atom. Eq. (6) was first derived by Zernike and Prins[2] and was first applied by Debye and Menke[3] in an x-ray study of liquid mercury.

Fourier Analysis of Vitreous SiO_2

A simple stable glass, and one that is very convenient for x-ray study, is vitreous silica (fused quartz). For the details of the analysis reference should be made to the original paper.[4] The diffraction patterns were made in an evacuated camera of radius 4.40 cm, using Cu$K\alpha$ and Mo$K\alpha$-radiation, made essentially monochromatic by reflection from a rocksalt crystal. Intensity curves were obtained from the microphotometer records of the diffraction patterns.

The final scattering curve for vitreous SiO_2 is shown in Fig. 1. This curve is put upon an absolute basis (electron units per SiO_2) by consideration of the fact that at large values of $\sin\theta$ it must approach the curve for independent scattering by the atoms. Subtracting the Compton modified scattering, one plots the curve $si(s)$, and carries through the integration involved in Eq. (6) either graphically or with a harmonic analyzer.

For a material containing more than one kind of atom, such as SiO_2, Eq. (6) takes the more general form.[4]

$$\sum K_m 4\pi r^2\rho_m = \sum K_m 4\pi r^2\rho_0 + \frac{2r}{\pi}\int_0^\infty si(s)\sin rsds. \qquad (7)$$

$\sum$ indicates summation over the molecular composition,

K_m is the effective number of electrons in atom m,

ρ_0 is the average number of electrons per unit volume.

Figure 2 gives the radial distribution curve for vitreous silica, $\sum K_m 4\pi r^2\rho_m$ plotted against r. Since there are two kinds of atoms in this case, the curve is really two curves superimposed, the distribution about a silicon and the distribution about an oxygen. The positions of the peaks give the distances of atoms from a silicon or an oxygen. From the area under the peaks, it is generally possible to calculate the number of neighbors at that distance.

The first peak occurs at about 1.62A, in good agreement with the average silicon oxygen distance 1.60A found in crystalline silicates. From the area under the first peak we can calculate the number of oxygens about any silicon. If there are n oxygens about each silicon, there must be $n/2$ silicons about each oxygen. From the atomic scattering factors for silicon and oxygen it is found that the best average value for the effective number of electrons per atom is for silicon $K=16.0$ and for oxygen $K=7.0$.

The area under the first peak will be

$$A=1\times16\times n\times7.0+2\times7.0\times(n/2)\times16.$$

Equating this to the observed peak area 970 elect^2 and solving for n

$$n=\frac{970}{1\times16\times7.0\times2}=4.3\sim4.$$

Since the silicon atom is always found tetrahedrally surrounded by four oxygens at a distance of 1.60A in all crystalline silicates it seems likely that the value 4.3 should be interpreted as 4. If each silicon is tetrahedrally surrounded by 4 oxygens, each oxygen must be bonded to 2 silicons. If the 4 oxygens about a silicon are tetrahedrally arranged, then the next larger interatomic distance will be the oxygen-oxygen separation, and this should be

$$1.62(8/3)^{\frac{1}{2}}=2.65\text{A}.$$

The second and third peaks are not well resolved, but the existence of a peak at about 2.65A of about the right area is clearly indicated.

Assuming that the two bonds to an oxygen are roughly diametrically opposite, the next few interatomic distances are readily calculated. These distances are indicated on Fig. 2 by a series of vertical lines, the heights of the lines being proportional to the expected peak areas. The oxygen-second oxygen distance depends upon the relative orientation of two tetrahedral groups about their connecting Si−O−Si bonds, and the value 4.5A which is given represents only an average distance. The peak at about 4.2A in the experimental curve is interpreted as an unresolved average of the Si−O peak at 4.0A and the average O−O separation of 4.5A. For distances greater than about 6.0A the interatomic distances depend upon the relative orientation of the tetrahedral groups, and the distribution curve rapidly smooths out.

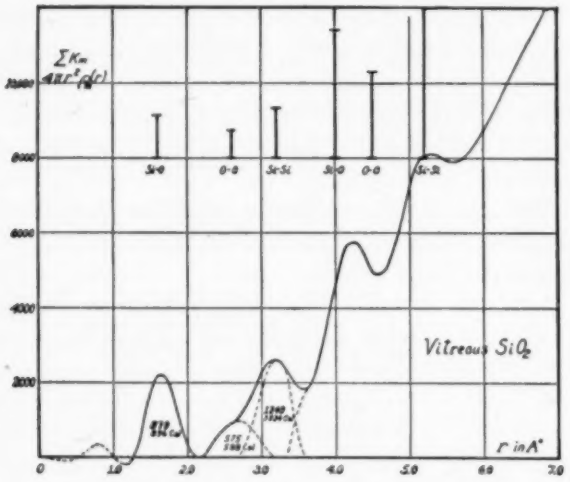

FIG. 2. Radial distribution curve for vitreous SiO_2.

It should be pointed out that the distribution curve of Fig. 2 is a unique result for vitreous silica, since the application of the Fourier method of analysis involves no assumption as to whether the material is truly amorphous or crystalline. The x-ray results are completely explained by picturing glassy silica as a random network in which each silicon is tetrahedrally surrounded by four oxygens, each oxygen bonded to two silicons, the two bonds to an oxygen being roughly diametrically opposite. The orientation of one tetrahedral group with respect to a neighboring group about the connecting Si−O−Si bond can be practically random. This is the simplest picture of silica glass, free from all specialized assumptions, which will completely explain the x-ray diffraction pattern. There is a definite scheme of structure involved, each atom has a definite number of nearest neighbors at a definite distance, but no unit of structure repeats itself identically at regular intervals in three dimensions, and hence the material is not crystalline. This is essentially the picture of an oxide glass which Zachariasen arrived at from consideration of the chemical composition. Fig. 3 taken from Zachariasen's paper[5] illustrates schematically in two dimensions the irregular structure of a glass as distinguished from the regularly repeating structure of a crystal.

The Crystallite Theory of Glass

While the Fourier method gives uniquely the coordination scheme, that is the number of neighbors and their distances, it does not answer the specific question as to whether or not the material can be considered crystalline. A number of workers have interpreted the x-ray diffraction patterns of vitreous silica as due to extremely small crystals of the high temperature crystalline form of silica, cristobalite.[6, 7]

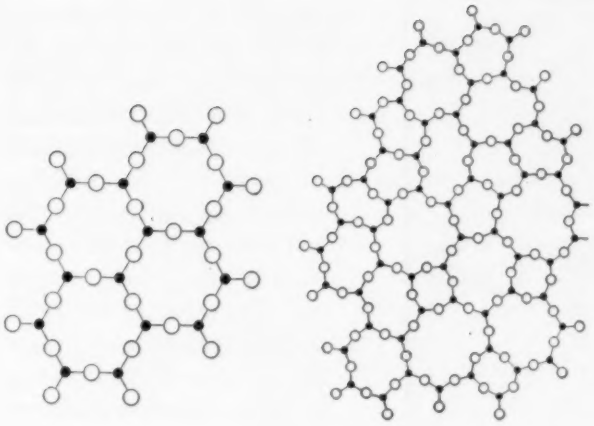

FIG. 3. Schematic representation in two dimensions of the difference between a crystal and a glass. (a) Crystal, (b) glass (W. H. Zachariasen).

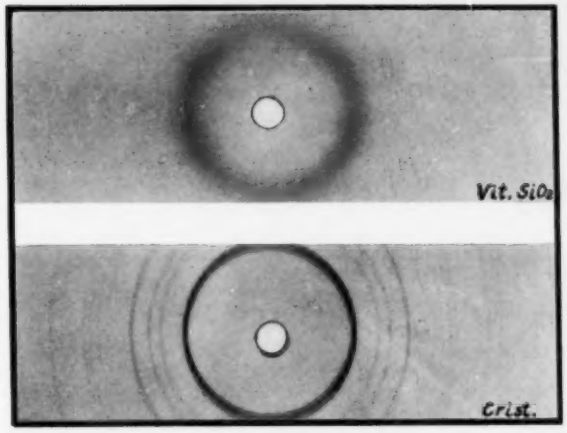

FIG. 4. X-ray diffraction patterns. (above) Vitreous silica, (below) cristobalite.

Figure 4 shows the diffraction patterns of vitreous silica and cristobalite taken under identical conditions. Fig. 5 shows the microphotometer records of these patterns. The strongest ring in the cristobalite pattern comes at very nearly the position of the first broad peak in the vitreous silica pattern. Since the breadth of the lines on a powdered crystalline pattern increases continuously with decreasing size of crystalline particles, it is evident that if one postulates in vitreous silica cristobalite crystals sufficiently small, the strong peak of cristobalite would broaden out to give the appearance of the vitreous pattern. From a formal point of view this interpretation is perfectly sound, and since cristobalite is the stable form of silica through the temperature range in which the glassy SiO_2 stiffens up, it is not at all unreasonable to expect cristobalite crystals in the glass.

Let us assume tentatively that the x-ray pattern of vitreous silica is actually due to small cristobalite crystals, and see what conclusions can be drawn. Changing the microphotometer records to intensity curves, and measuring the half intensity breadth of the peak, we can calculate the average particle dimension by the Bragg particle size equation.[8]

$$L=\frac{0.89\lambda}{B\cos\theta}=\frac{0.89\times 1.54}{0.181\times 0.98}=7.7\text{A}.$$

Since the edge of the unit cell of cristobalite is about 7.0A we are forced to postulate cristobalite crystals comprising scarcely more than one unit cell in order to explain the observed peak width. Since the essence of the idea of crystallinity is regular repetition it becomes decidedly artificial and formal to extend the term crystal to cover so small an aggregation of atoms.

For the sake of argument let us continue to assume that vitreous silica consists of small crystals of cristobalite. The next question to be answered has to do with how these assumed crystallites join onto one another. Is the glass an aggregation of these small crystals with some kind of break in the bonding between them, or is the scheme of bonding perfectly continuous with no breaks or voids? In other words, is glass like a pail full of pebbles or like a pail full of water? This can be answered by consideration of the small angle x-ray scattering. Fig. 5 (c) shows the pattern of a commercial silica gel. The main peak is roughly the same as that for the glass, but for the gel there is a very strong small angle scattering which is completely absent in the glass. Small angle scattering is due to large scale inhomogeneities in the sample, and in the case of the silica gel is presumably due to the existence of discrete particles (10–100A) with breaks and voids between.

Since there is no small angle scattering in the glass the scheme of bonding must be essentially continuous. Going out from an assumed cristo-

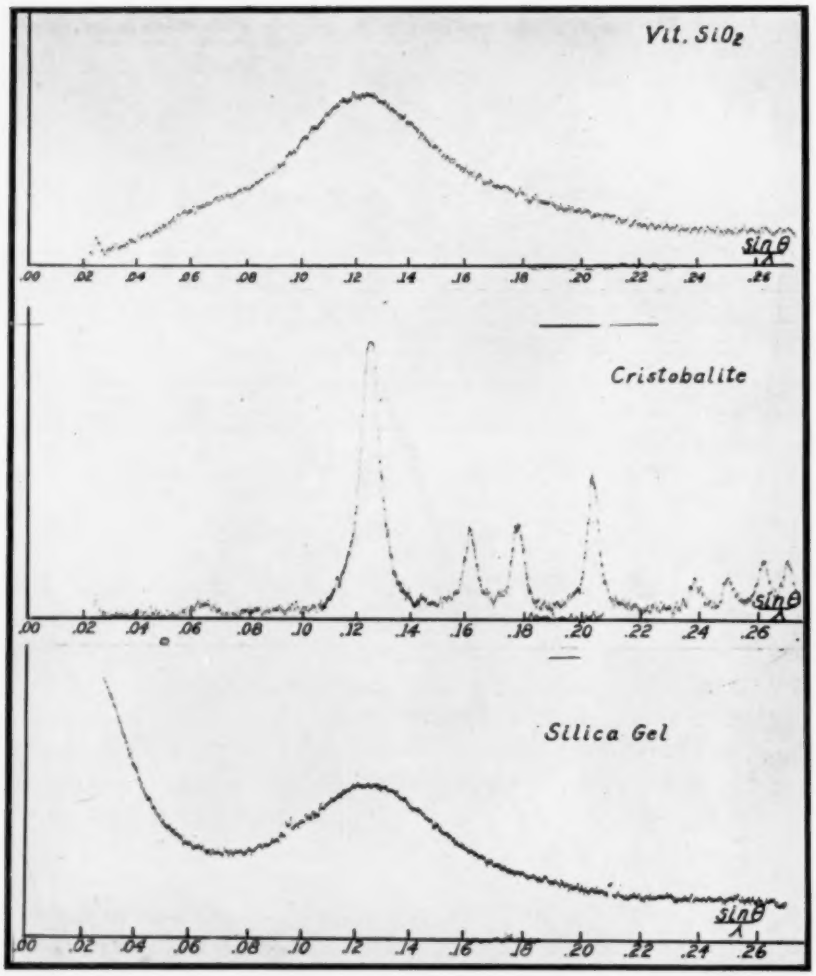

FIG. 5. Microphotometer records of x-ray diffraction patterns. (a) Vitreous silica, (b) cristobalite, (c) dried commercial silica gel.

balite crystal the scheme of bonding cannot follow the crystalline pattern for otherwise the peak breadth would be different from the observed value. Considering the small size of the crystallites and the relatively thick layer of noncrystalline continuous network necessary to bond together continuously two separate crystals, one is forced to conclude that even though he postulates cristobalite crystallites in the glass, only a small fraction of the material could be in this form.

Discussion of the Structure of Glass

Although a number of workers have tried to explain the x-ray diffraction patterns of glass as due to extremely small crystals, the objections which have been brought out in this discussion appear to be much too severe to accept this picture of the glassy state. The crystallite theory leads to a size of crystalline particle so small that to call it a crystal is stretching the term so far that it ceases to have any definite meaning. The absence of small angle scattering means that the glass is a continuous medium with no discrete particles or breaks in the scheme of bonding. Therefore even if one assumes tiny cristobalite crystals in the glassy silica only a fraction of the material could be in this form. On the basis of the crystallite theory one is still left with the problem of explaining an extremely small and approximately constant particle size in order to explain the peak width.

X-ray analysis does not prove that there is no crystalline cristobalite in glassy silica. Here and there one would expect to find the cristobalite configuration existing for a short distance as one of a continuous variety of configurations. The x-ray analysis does, however, prove that the major part of the material cannot be in the form of cristobalite crystals of sufficient size to give the term any meaning.

The scheme of coordination about each atom is the same in silica glass and in crystalline cristobalite. If a man sitting on a silicon atom could look no farther than the nearest and next nearest atoms, he would not know whether he was in a piece of silica glass or in a cristobalite crystal. The glass is a form of matter in which the coordination scheme is the same as in the crystalline phase, but which cooled too rapidly from a viscous melt to allow the orderly building up of a regularly repeating structure to any

appreciable extent. In other words, glass is a liquid of extremely high viscosity in which the atoms are too tightly tied together in an irregular network to allow the breaking up and reforming necessary for crystallization.

The term random network has been suggested to express this picture of the glassy state. There is a definite scheme of coordination and a continuous system of bonding with no breaks or discrete particles, and yet no unit of structure repeats itself identically at regular intervals so that the material is noncrystalline. This is the simplest picture of the glassy state which will completely explain the x-ray diffraction results. In addition it is a picture which differs sufficiently from the picture of a crystalline material to allow an understanding of the very definite differences which do exist between the glassy and crystalline states.

The remarkable glass forming properties of silica are due to two features which result from the coordination scheme. Even in the melt there is probably a strong tendency for each silicon to surround itself by four oxygens and hence for each oxygen to bond between two silicons. Although any such bonding must be continually forming and breaking, it will nevertheless put enough linkages into the melt to stiffen it up and give the high viscosity which prevents the atoms from pulling apart and reorganizing. It is this factor which prevents crystallization on cooling. The fact that each oxygen is bonded to only two silicons puts such a flexibility into the

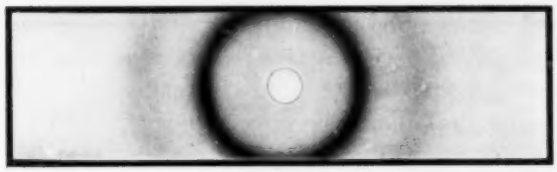

FIG. 6. X-ray diffraction pattern of liquid sodium.

scheme of structure that the random network is almost as stable as a crystalline arrangement and can therefore continue to exist. While most commercial glasses contain several constituents the predominant constituent is silica, so that a clear understanding of the constitution of silica glass has been a necessary first step in an investigation of the general problem of the glassy state.

X-Ray Analysis of Liquid Sodium

The simplest liquid that is well suited to an x-ray diffraction study is probably liquid sodium.[9] The x-ray absorption is small and it melts at a convenient temperature. The material was contained in an evacuated thin-walled Pyrex tube

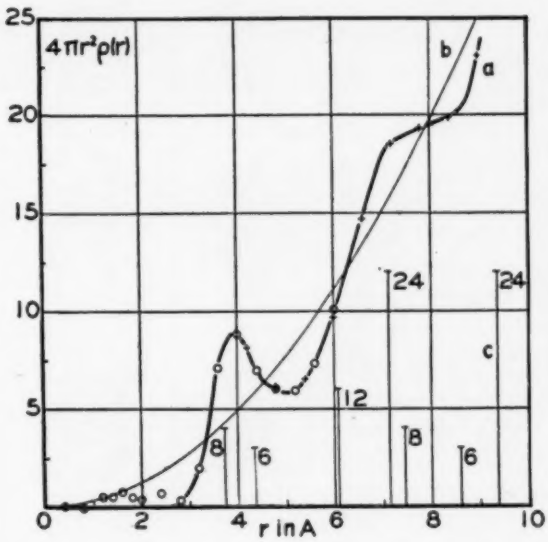

FIG. 7. (a) Radial distribution curve for liquid sodium $4\pi r^2\rho(r)$. (b) Average density curve $4\pi r^2\rho_0$. (c) Distribution of neighbors in crystalline sodium.*

of diameter 2.0 mm and maintained at a temperature of 103°C. The pattern was made with Mo$K\alpha$-radiation monochromated by reflection from a rocksalt crystal. The cylindrical camera was of radius 8.61 cm. Fig. 6 shows the diffraction pattern of liquid sodium.

Carrying through the Fourier analysis in the usual way, one obtains the radial distribution curve shown in Fig. 7. This curve gives the number of sodium atoms to be found at any distance from a given sodium atom. There is a marked concentration of atoms at a distance of about 4.0A and beyond this a slight dip.

The resulting density curve is conveniently interpreted in terms of a box full of ball bearings continuously shaken. About the center of any one ball bearing we will never expect to find another closer than the diameter of the balls. At about this distance we will expect to find the centers of several balls, since at any instant there will be a

* In Fig. 7 (a), as well as in the original paper,[9] there is an error of about 2.5 percent in the scale of abscissae. All distances read from 7 (a) should be 2.5 percent smaller.

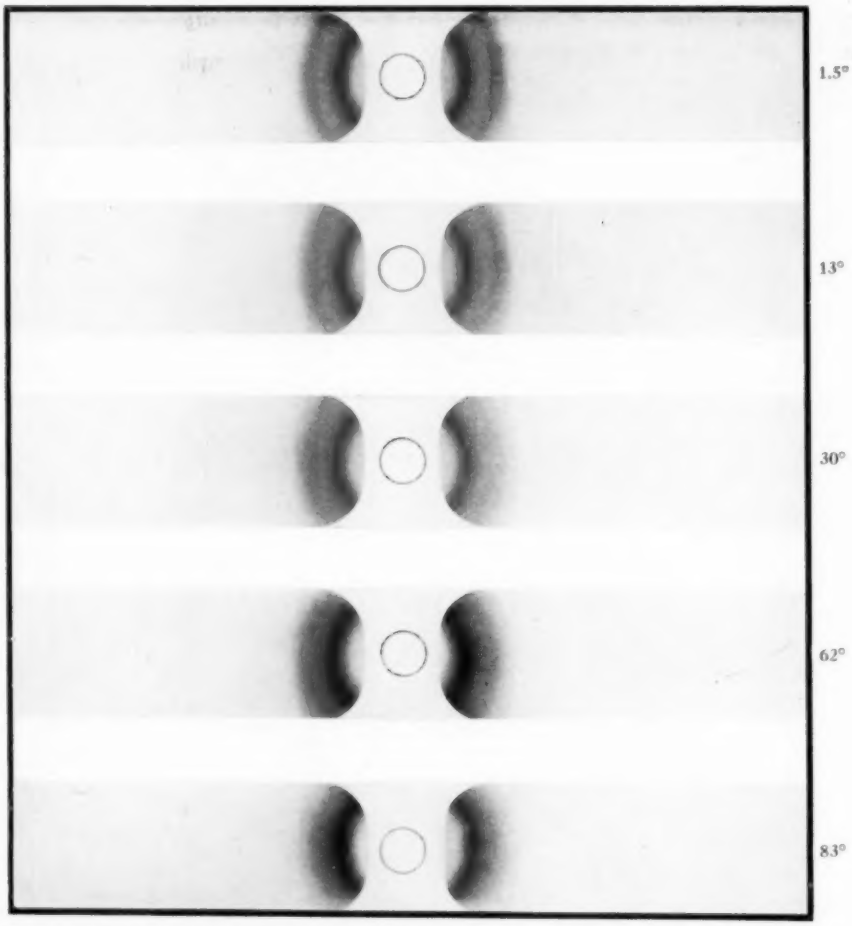

FIG. 8. X-ray diffraction patterns of water at temperatures: 1.5°, 13°, 30°, 62°, and 83°C. (Morgan.)

number of balls in approximate contact with the one under consideration. At a somewhat larger distance the number of balls must drop a little since the balls already considered prevent others from coming into the immediate vicinity of the first ball.

For a simple monatomic liquid such as liquid sodium, this appears to be the simplest picture which is in agreement with the x-ray results. It is evident that there is such a thing as a structure in the liquid; a structure which has to do with the average distribution of neighboring atoms about any one atom. The existence of such a structure could be inferred from the fact that in a crystal the atoms are rather closely packed and in contact, and the density of liquids is not very different from that of the corresponding solids. The x-ray analysis of liquids will be of help only to the extent that it succeeds in giving a detailed picture of this structure.

X-Ray Diffraction Study of Water

Morgan has recently completed a careful x-ray study of water.* Fig. 8 shows the diffraction patterns for five different temperatures. With increasing temperature the second ring becomes less and less sharp, indicating a gradual washing out of the sharp structure which exists in water at low temperature.

In Fig. 9 are shown the radial distribution curves for water obtained by a Fourier analysis of the x-ray scattering patterns. The nearest neighbor peak varies from about 2.9A to 3.0A. This distance is somewhat larger than the O—O distance in ice 2.76A. From the area under the first peak there are roughly 4 neighbors about each water molecule.

There is one definite difference between the distribution curves for glasses and liquids. In a glass any atom has permanent nearest neighbors at a definite distance and this shows up in the distribution curve for vitreous silica, Fig. 2, by the fact that the first peak is completely resolved. In all the glasses so far studied the dip following the first peak comes down approximately to the axis. On the other hand, in simple monatomic liquids the first peak is never well resolved, the dip coming down not more than halfway to the axis. This important point is clearly seen in the distribution curves for sodium and water. The obvious interpretation is that in liquids a mole-

* A complete report of this work will be published soon. I am indebted to Dr. Morgan for permission to include these diffraction patterns and density curves.

cule does not have permanent neighbors. At any instant we will find a few neighbors in approximate contact and others at greater distances which are either on the way in or the way out.

Although the area under the first peak is not very definite, it gives approximately four for the number of nearest neighbors. However this should probably not be interpreted as meaning that in water each molecule is tetrahedrally bonded to four neighboring molecules, and each of these to four, and so on. It is more likely that at any instant there will be less than four neighbors in approximate contact, and an indefinite number of neighboring molecules which are moving in or out. In other words, the tendency of a water molecule toward tetrahedral coordination still persists in the liquid but not strongly enough to maintain four bonded neighbors about each molecule. This view is substantiated by the fact that from Raman spectrum studies[10] there is strong evidence that an appreciable fraction of the molecules are at any instant only two coordinated.

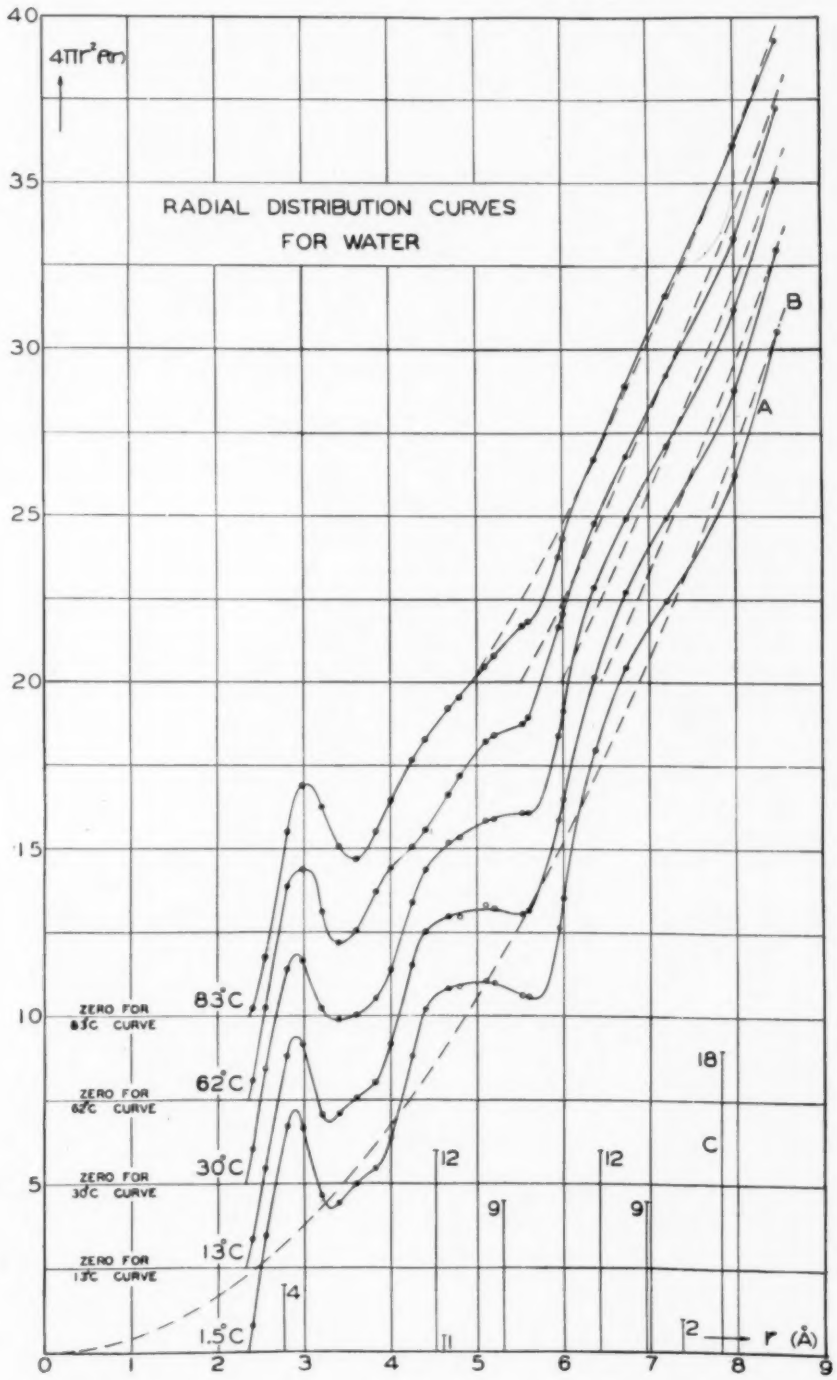

FIG. 9. Radial distribution curves for water at different temperatures obtained by Fourier analysis. (Morgan.)

If all of the water molecules were four coordinated as in ice it would be difficult to understand the latent heat of fusion, but if the average number of bonded neighbors in water is less than four, the heat of fusion is readily explained by the broken bonds. That the density of water is greater than that of ice is due to the fact that the crystal structure of ice is an unusually open structure resulting in a very low density. Even though the nearest neighbors are at slightly larger distances in water than in ice, the breaking down of the skeleton ice structure allows molecules at distances between those of the first and

second neighbors in the ice structure. This filling in more than compensates the expansion in interatomic distance and results in the higher density of water. A complete presentation of the x-ray studies of water will be published soon by Morgan.

General Remarks

In a liquid the number of nearest neighbors and the interatomic distances are roughly the same as in the crystalline material. This is, of course, the reason why the density of liquids does not differ greatly from that of the corresponding crystals.

A number of times the observation has been made that the rings of a liquid or glass diffraction pattern come rather closely at the position of the strongest lines or group of lines in the powder pattern of the crystalline material. It has been suggested that this indicates that an essentially crystalline type of structure exists in the liquid. From the point of view of the Fourier analysis, however, this simply means that the radial distribution curve will show peaks at about the same position. This means roughly the same interatomic distances, and this is just another way of expressing the fact that the density of the liquid is not very different from that of the solid.

Prins and Petersen[11] have found that if one takes the radial distribution of the crystal and smooths it out a little, the x-ray diffraction pattern calculated from this distribution function agrees well with the experimental patterns of the liquid. This is another statement of the fact that the interatomic distances and coordination numbers are not very different in the liquid and the solid.

The study of liquids and glasses has suffered considerably from the use of loose terminology. Terms such as pseudo-crystalline or quasi-crystalline have no definite meaning unless they are specifically defined, and it is rare indeed for anyone using such terms to bother to specifically define them. The term crystalline has a very definite meaning, and expresses the idea of a unit of structure being repeated identically at regular intervals in three dimensions. There is no excuse for calling a material crystalline when one is merely trying to express the idea that it has roughly the same coordination number, or interatomic distances, or density as found in the crystalline form. That there is a close relationship in properties such as these between the liquid and the crystalline states is obvious from elementary considerations of density. The whole point to the study of the structure of liquids is *to find out precisely what are the differences between the liquid and the crystal.*

Three specific examples have been cited in this report: vitreous silica, liquid sodium, and water. These will perhaps suffice to illustrate the methods of analysis and the kind of information that it is now possible to obtain from the x-ray diffraction study of noncrystalline materials.

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Production and Absorption of Electromagnetic Waves from 3 cm to 6 mm in Length*

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JUST what is meant by short electromagnetic waves depends upon one's point of view. The amateur radio operator thinks of 25 meter waves as short waves, and so, as it became possible to produce waves of one meter length, a new name was invented for them and they were called microwaves. There seems, therefore, no name left that will apply to waves whose lengths are measured in millimeters.

In 1919 Barkhausen and Kurtz described a method of producing radiation having a wave-length less than a meter. They used a three electrode tube with the grid at high potential and the plate at low potential. Work with oscillators of this kind now constitutes a standard experiment in courses on high frequency measurements in many universities. In 1921 A. W. Hull described the magnetron, a two-electrode tube with a magnetic field applied approximately parallel to the filament. He derived the value of the magnetic field which would cause the electrons from the filament to move in a spiral around the filament and just graze the surface of the cylindrical anode. This value is

$$H=(8m/e)^{\frac{1}{2}}V^{\frac{1}{2}}/R.$$

Putting in the value of m/e, this reduces to

$$H=6.72(V)^{\frac{1}{2}}/R,$$

in which V is the potential difference in volts between cathode and anode, and R is the radius of the anode. Hull's experiments showed a sharp cut-off of current when this field was applied. He did not use the tube as an oscillator but merely as a device in which a magnetic field controls the current. The expression for the magnetic field intensity is utilized in determining the approximate intensity of field that is applied to the oscillators which we are about to discuss.

In 1928 and the years immediately following, Yagi and Okabe and others used tubes like those of Hull's as oscillators, and were able to produce continuous radiations having wave-lengths as low as ten cm. These waves should be distinguished from those produced by Nichols and Tear by means of an oscillator using a spark gap. While these waves of Nichols and Tear were extremely short, having lengths as low as 1.8 mm, both the intensity and the wave-length were so variable that it was not possible to use them in researches requiring constant intensity and constant wave-length.

The tube as used at the present time has a split anode as shown in Fig. 1, the two halves of the anode being connected through a short Lecher frame. The anode is held at a potential with reference to the filament of from 500 to 1400 volts, depending upon the wave-length to be produced. The magnetic field is adjusted to very nearly the cut-off value. Any slight increase

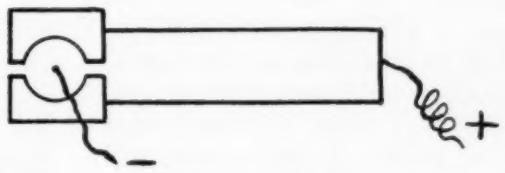

FIG. 1. Diagram of tube with split anode which is used at the present time.

* Presented at the Madison, Wisconsin meeting of the American Physical Society, June 22–23, 1937.

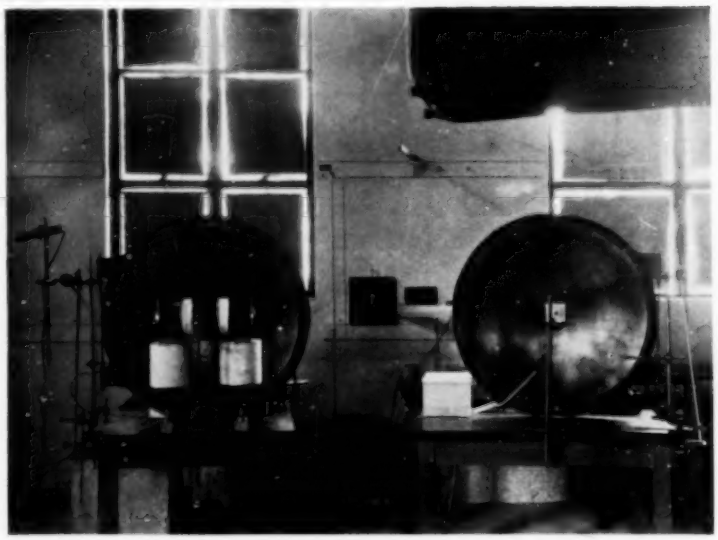

FIG. 2. Source and detector for 1.5 cm electromagnetic waves.

of potential of one-half of the anode will cause the electron stream to be deflected to that half. This lowers the potential of that half and the electrons are repelled to the other half. A surge in the frame connecting the two halves is thus set up. It will be evident that two items enter into the determination of the frequency of the oscillations, *viz.* the time of flight of the electron from one-half of the anode to the other and back, and the time determined by the *LC* product of the circuit. When these two values are equal, the conditions are right for producing a large amplitude. Okabe reported as the shortest wave that he produced by tubes of this kind, a length of 3.16 cm.

Our own interest in producing short wave radiation grew out of the prediction by Dennison of the Michigan laboratory that ammonia gas should absorb waves 1.5 cm long. Kilgore had worked with tubes at the Westinghouse laboratory that gave considerable power at a wave-length of 9 cm. It seemed reasonable to assume that smaller tubes, operating on higher voltages and with stronger magnetic fields, would oscillate at higher frequency. C. E. Cleeton, at that time a graduate student at Michigan, undertook to build the tubes. He became very expert in this work and finally carried out the research on ammonia gas. The wave-lengths were so near to those that had been used in infrared work that optical methods immediately suggested themselves. The tube was mounted at the focus of a mirror 3 feet in diameter. The radiation was directed across the room to an echelette grating 25 feet away. From there it was reflected to another large mirror and focused upon a crystal detector. Figs. 2 and 3 show this part of the apparatus. A crystal must be used that does not require a voltage bias. Iron pyrite-phosphor-bronze was found to be the best. The grating gave a very satisfactory measurement of the wave-length. The elements of the grating were strips of aluminum $7\frac{1}{2}$ by 70 cm, and there were 18 such strips in the grating. The elements of the grating were automatically adjusted to remain perpendicular to the bisector of the angle between the lines from the center of the grating to the centers of the mirrors. The spectrum was pure and as many as seven orders could be measured. The accuracy of the wave-length measurement was better than one percent. Fig. 4 shows the seven orders of spectra for a wave-

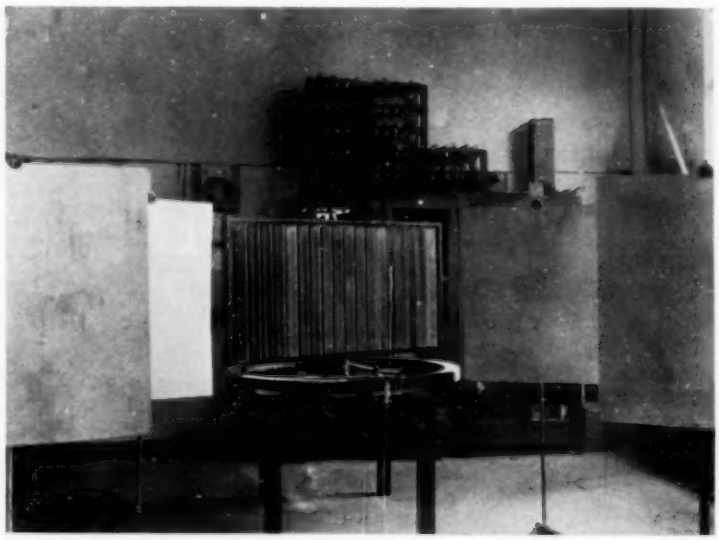

FIG. 3. Echelette grating for 1.5 cm electromagnetic waves.

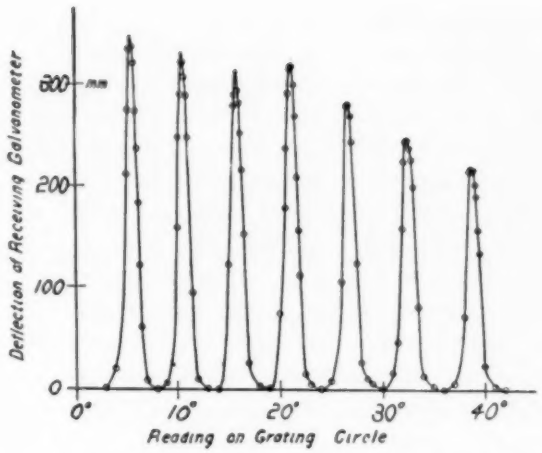

FIG. 4. Seven orders at 1.33 cm as given by the echelette grating.

length of 1.33 cm. This tube had an anode radius of 0.027 cm and required an anode potential of about 800 volts. The Lecher system had a length of about four mm. Each tube could be made to operate over a range covering about 30 percent of the mean frequency. Four tubes were used in making the absorption measurements between wave-lengths of 1.06 and 3.8 cm. To study the absorption due to ammonia gas, a cell somewhat larger than the mirrors and having a thickness of 16 inches was used. This could be lowered in front of the receiving mirror and the absorption observed. After a series of measurements with the ammonia, the cell was filled with air and the small absorption due to the rubber was measured. The ammonia absorption data were then corrected for the absorption due to the cell. The absorption as a function of the frequency is shown in Fig. 5. The maximum absorption occurs very nearly at the point predicted by Dennison. Fig. 6 shows the percentage of absorption as a function of the wave-length.

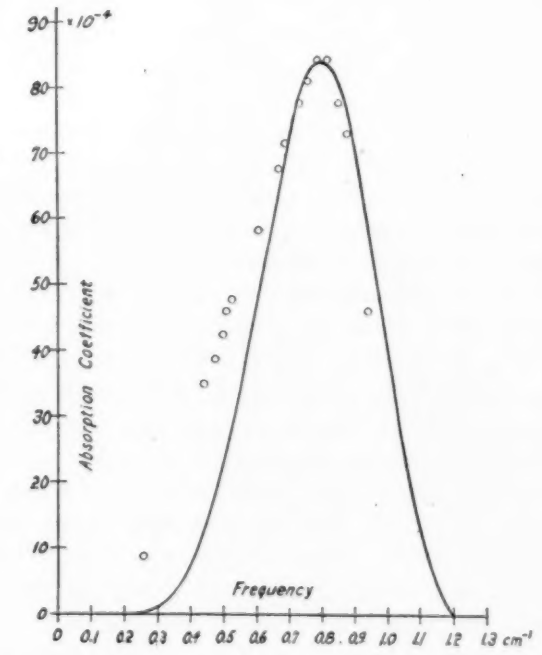

FIG. 5. The theoretical absorption curve for NH_3 and the observed experimental points plotted on a frequency scale.

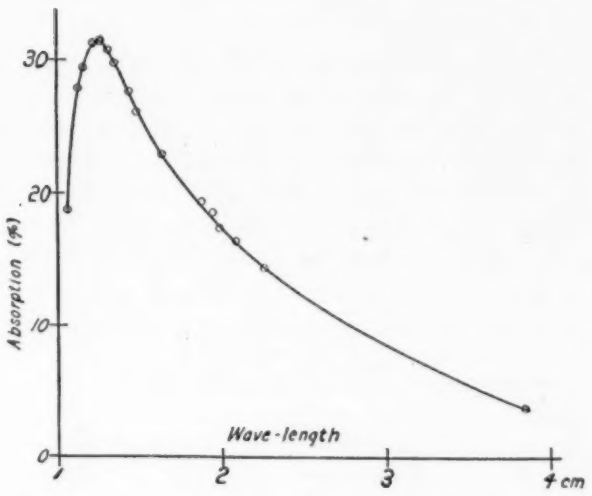

FIG. 6. The absorption band of NH_3 plotted on a wave-length scale.

Dr. Cleeton was still at the Michigan laboratory last summer, and we undertook, at that time, the problem of finding out the practical limit of frequency that may be produced by magnetron tubes. The tubes were already so small that they were difficult to build, but the limit had not been reached. Dr. Cleeton made a number of smaller tubes and the data for some of them are given in Table I. It will be observed that the radius of the anode for the tube giving the shortest wave-length is only 0.2 mm, and that the Lecher system is less than 4 mm in length. The tube was literally built under a microscope. The fact that the radiator is so small of course means that very little energy is radiated. This is sufficient to discourage one from trying to go farther.

TABLE I.

R_a	L	V	H	λ
0.045	0.99	830	6,600	1.87
0.035	0.75	1350	9,900	1.22
0.019	0.38	1200	24,000	0.64

R_a is the anode radius in cm, L is the distance from the filament to the end of the frame, V is the anode potential in volts, H is the magnetic field strength in oersteds, and λ is the wave-length in cm.

Several modifications of the apparatus already described have been made. For example, the magnet and the tube were put behind the mirror and the energy was conducted by concentric conductors through a hole in the mirror to its focus. This avoided covering a large portion of the mirror surface by the magnet, and thus increased the radiation. This apparatus was used in studying the possibilities of modulating the

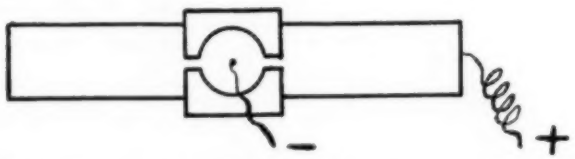

FIG. 7. Diagram of a tube with 2 Lecher systems connected to the halves of the anode.

waves. Speech and music were successfully transmitted at a wave-length of a few cm.

A change in the design of the tube was also tried. Two Lecher systems were connected to the halves of the anode, so that the tube appeared as in Fig. 7. These tubes worked well but there was no marked improvement in the results.

One of the significant features of the work on short electromagnetic waves is that it opens a new region of the spectrum for quantitative study. Possibly it will not be a very exciting region, since it forms the link between the shorter electric waves and the longer heat radiation, and hence its properties may be estimated by interpolation. Nevertheless, it does allow us to investigate the behavior of matter to a band of frequencies which up until now have been inaccessible. In fact, as has already been mentioned, the strong initial motive for attempting to produce short waves was the desire to test a hypothesis concerning the structure of the ammonia molecule. It had been pointed out by Dennison that there was spectroscopic evidence which indicated that the normal energy state of ammonia might be double. The separation between these levels was about 0.7 cm^{-1} and hence the gas should strongly absorb radiation of 1.4 cm wave-length. As you know, this prediction was beautifully and completely verified by experiment. A cell six times as thick as the ammonia cell was filled with saturated water vapor and put into the path of the rays. Theory would lead us to expect no absorption in this case and none was found. It is now interesting to enquire whether other gases may be expected to absorb in this region. The two energy levels which exist in ammonia are a consequence of the fact that there are two entirely equivalent equilibrium positions for the nitrogen atom separated by a low potential barrier. If we think of the hydrogen atoms as forming an equilateral triangle, the nitrogen atom is not at the center of this triangle but is displaced from the plane of the hydrogen atoms, thus giving the molecule the shape of a pyramid. The equilibrium positions referred to are on opposite sides of this plane. The frequency of the transition is closely related to the ease with which the nitrogen atom can penetrate the barrier, and is a very sensitive function of the molecular dimensions. Thus if the height of the pyramid which represents the ammonia molecule should be decreased by 20 percent, the wave-length corresponding to absorption would change from 1.4 cm to 0.07 cm, which is quite outside the present experimental range. If the height of the pyramid were increased by 20 percent, the absorption wave-length would become 42 cm, which would appear to be easily observable. However, a simple calculation shows that for this type of transition, the absorption is inversely proportional to the square of the wave-length. Thus an absorbing column of gas 1000 or more meters long would be required. The conclusion which we reach is that the molecule of ammonia is ideally designed for an initial experiment on the absorption of short waves. We know of no other molecule which possesses these properties, and it is unlikely that one exists. Even the molecule ND_3 would have too long a wave-length, although possibly NH_2D might fall within the range of observability.

There are, however, other classes of transitions between the energy states of molecules which may be studied. One which suggests itself first

results in rotational frequencies. Molecules which are only moderately large, as for example, the methyl halides, will possess rotational frequencies in the region of one cm waves. A knowledge of these would be very useful, since it fixes one of the moments of inertia of the molecule. Professor Dennison has calculated the length of path in the gas which is necessary in order to insure an absorption of 50 percent at the center of the line. He informs me that he finds

$$l = 2000(\lambda^3/(M_0)^2),$$

where λ is the wave-length in cm and M_0 is the permanent electric moment of the molecule in units of 10^{-18}. For the methyl halides, $M_0 \backsimeq 1.5$ and consequently at $\lambda = 1$ cm, we should need a path length of 9 meters, while at $\lambda = 2$ cm, $l = 72$ meters. It is quite evident that no ordinary absorption cell can be used. At the University of Michigan we are now attempting this experiment. We propose to use guided waves where the wave guide will be a conducting tube which will serve as the absorption cell. Clearly the success of our attempt will depend upon just such studies of guided waves as are to be discussed here today.

A second and an interesting field for the application of short waves is the investigation of the absorption and refraction of waves by liquids and solids. Last year Dr. Knerr, working with the apparatus just described, measured the refractive index of water in the region from 4 to 20 cm wave-length. He found that for these waves water shows no measurable dispersion, the index remaining constant at 8. The absorption coefficient, however, increases rapidly as the wave-length decreases. Obviously this research has a bearing upon the theory of liquids, in particular upon Debye's dipole theory. It will be desirable to extend this work to electrolytes and to other liquids which possess dipoles.

In conclusion we may say that the work already done on short waves has been fruitful and it bears promise of becoming increasingly so. A study of the production of the waves sheds light upon phases of the problems of electronics and vacuum tubes. Many interesting questions must be answered before still shorter waves can be obtained. On the other hand we may expect that the waves will furnish us with useful information concerning the structure of molecules as well as concerning molecular aggregates as they occur in liquids and solids.

It is also probable that these very short waves will make important contributions to certain practical problems. They may be used in communication over short distances by means of a directed beam. The frequency band which they represent is so broad that many channels are possible in a narrow range of wave-lengths. Again as a directed beam they may play a role in solving the problem of seeing through fog. However, these are mere speculations and much arduous research would be necessary before results could be realized.

This new ability of man to create, and the new vision it has given us, in turn is creating a new economy—an economy that is putting wealth, in the true sense of greater enjoyment of life, within the reach of millions who never before knew it, that is creating new opportunities for work, new leisure, new health. Above all it is creating new knowledge in the light of which almost nothing stands as impossible.

—C. M. A. STEIN

New Experimental Methods Applicable to Ultra-Short Waves*

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Introduction

THE principles underlying wave guide transmission, a novel form of electrical transmission for which experimental results were recently reported,[1] appear to offer a new approach to the problem of high frequency electrical measurements. In this form of transmission certain configurations of electric and magnetic force are propagated as waves through cylinders of dielectric. A special case is, of course, that where the dielectric is air. For this case a metal sheath is necessary.[2] If, however, the dielectric constant is high the sheath may not be altogether essential.

The present paper describes some of the early steps which have been taken at the Bell Telephone Laboratories in the application of these principles to high frequency electric measurements in the hope of extending the range materially beyond the present rather indefinite frontier of about 10^9 cycles per second. The simple hollow pipe, which is perhaps the most convenient form of guide for laboratory use, will be assumed throughout this paper. For this case the diameter must be at least 0.58 wavelength.

One advantage of this new method is that if necessary both the source and the sink of high frequency power may be located entirely within the guiding structure thereby eliminating many of the difficulties incidental to radiation loss and to the spurious coupling effects that are common in ordinary high frequency work. It also turns out that the resistance losses in the walls of a metal pipe may be made less than the corresponding losses if the waves are propagated over a conventional circuit of either the parallel or coaxial conductor form. A better understanding of this method may be had by reviewing briefly some of the fundamental properties of wave guide transmission.

Forms of Waves

Theoretically at least, there is an infinite number of wave forms that may be propagated through guides of circular cross section. Each form corresponds to a particular solution of the differential equations appropriate to this problem. Four of these waves are of particular interest and have been made special objects of study in our laboratory. They may be distinguished by the configurations of the lines of electric and magnetic force of which they are comprised. These are shown in Fig. 1.

The first two waves have rather arbitrarily been designated as electric waves because there is a substantial component of electric force in the direction of propagation. For similar reasons the last two have been called magnetic. The subscripts are related to the mathematical expressions for these waves but they are also convenient reminders of their configurations. The experimental methods described below will be confined to the so-called H_1 wave.

* Presented at the Madison, Wisconsin meeting of the American Physical Society, June 22–23, 1937.

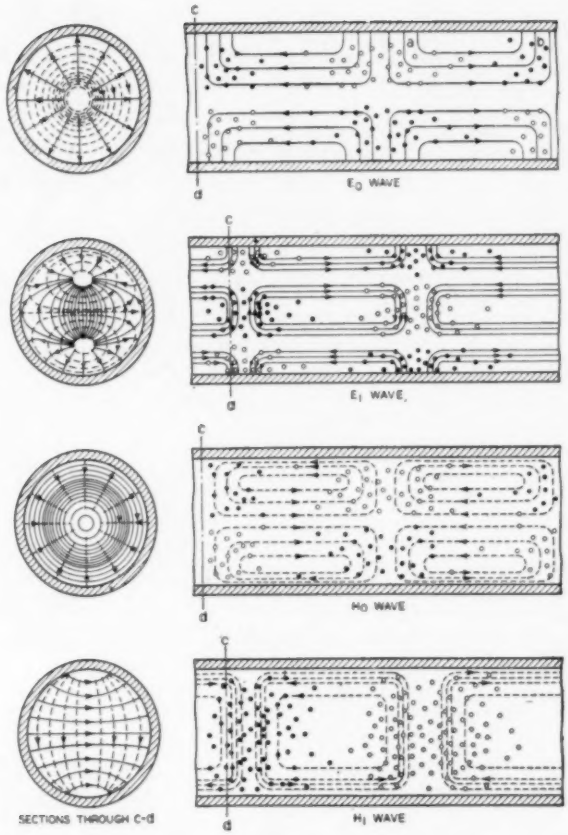

FIG. 1. Approximate configuration of lines of electric and magnetic force in a typical wave guide. Solid lines, lines of electric force; dotted lines, lines of magnetic force; black dots, toward observer; circles, away from observer.

Critical Frequencies

Electromagnetic waves may be freely transmitted in dielectric wires or hollow conductors only when the wave-length is less than a certain value set by the material of the guide and its dimensions. There is, therefore, for a given guide a critical frequency below which waves may not be propagated. We refer to this as the cut-off frequency. In a similar way we have for a given frequency, critical or cut-off diameters. These critical frequencies depend not only on the diameter (d) of the guide but on the dielectric constant (κ) of the medium as well. Also they are, in general, different for the different types of waves. For guides enclosed by a metallic conductor the cut-off wave-length is such that the circumference of the guide measured in wave-lengths is equal to the roots of certain Bessel's functions. These in turn result from solutions of the Maxwell equations expressed in cylindrical coordinates. These relations are shown more fully in Table I.

TABLE I.

Type of Wave	Bessel Function	Root	Cut-off Wave-length $=\pi d\kappa^{\frac{1}{2}}/X$
E_0	$J_0(X)=0$	$X=2.41$	$1.31d\kappa^{\frac{1}{2}}$
E_1	$J_1(X)=0$	$X=3.83$	$0.82d\kappa^{\frac{1}{2}}$
H_0	$J_{0'}(X)=0$	$X=3.83$	$0.82d\kappa^{\frac{1}{2}}$
H_1	$J_{1'}(X)=0$	$X=1.84$	$1.71d\kappa^{\frac{1}{2}}$

Most of our work has been done at frequencies between 2000 *mc* ($\lambda=15$ cm) and 6000 *mc* ($\lambda=5$ cm). For this range of frequencies the diameters of the guide range from about one to five inches (2.54 cm–12.7 cm). The methods which are described below are, of course, applicable to much higher frequencies such as for instance, the nearly 50,000 *mc* reported by Cleeton and Williams.[3] It is interesting to note that for this latter frequency ordinary hollow metal wire $\frac{1}{6}''$ inside diameter should be sufficient to guide these waves from one point to another.

The critical relations that must be satisfied before power may be propagated makes the wave guide essentially a high pass filter. This is a convenient property for laboratory use. By this means it is possible to reject in a wave guide all frequency components below a certain limit set by its diameter. Also it is sometimes possible to pass certain types of waves and reject others even though they be of the same frequency.

An example of the latter application will perhaps be in order. It was found that in a given source of H_1 waves operating on a wave-length of 15.5 cm there was an extraneous component of the E_0 type. The guide in which experiments were to be conducted was 12.5 cm in diameter and therefore capable of supporting both the wanted and the unwanted components. To obviate the difficulty a short section of pipe was introduced into the connecting line in which the diameter was slowly reduced from 12.5 cm to 10 cm and back to 12.5 cm. This throat was sufficient to suppress the E_0 component without seriously attenuating the desired H_1 curve. It would of course have been even more effective if the experiment itself had been conducted inside of a 10 cm pipe.

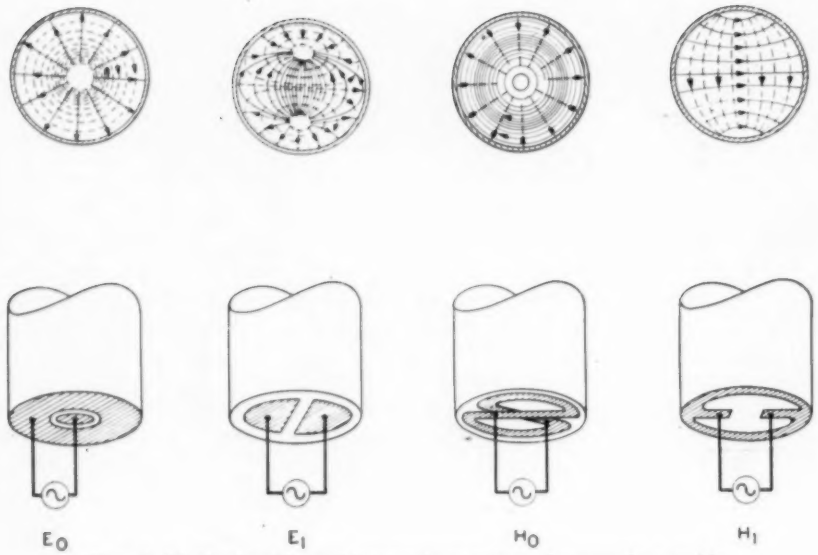

FIG. 2. Methods of launching various types of waves in a guide.

Resonance Effects

Short sections of wave guide may be made to resonate electrically much the same as organ pipes and air columns resonate acoustically. In the electrical case the resonant chamber is somewhat analogous to a tuned circuit consisting of a localized inductance and capacity. It is perhaps even more nearly analogous to a tuned Lecher frame. On account of the fact that both Joulian and radiation losses are low in the resonant chamber its degree of sharpness may be made very high.

In its role as a tuned circuit, the resonant chamber may be used in a variety of ways. It may either be a simple wave meter or a frequency determining unit for an oscillator. Also it may be used as an impedance matching device sometimes in connection with a generator (thereby enabling a vacuum tube to work more effectively) and sometimes as an element in a receiver (thereby impressing on a detector a maximum of received power). It is quite feasible also to use it as a means of impressing wave power on laboratory specimens that may be under investigation.

Generators

Figure 2 shows in a simple schematic way how each of these waves may be launched in a guide. Fig. 3 shows in greater detail how one of these methods is put into practice when the H_1 wave is desired. The terminals of the spiral grid of the Barkhausen tube are connected to diametrically opposite points on a pipe through a suitable by-pass condenser. The filament and plate leads enter along a plane perpendicular to that of the grid. Since the grid leads correspond to lines of electric force in the generated wave, the diametral plane perpendicular thereto corresponds to an equipotential. By locating the plate and filament leads in such an equipotential, their presence will not materially affect the normal field prevailing in the chamber. In the design shown the leads to one filament and the plate constitute the outside plates of a three-plate by-pass condenser. The third or central plate is a rigid member grounded on the main guide. It connects to the remaining filament lead of the Barkhausen tube. Connections to the exterior are had through five insulated binding posts. The oscillator unit shown carries on its exterior a plug connector leading by cable to a nearby d.c. power supply unit. Simple coils of wire of perhaps 10 turns each 1 cm diameter may be substituted for the three-plate condenser without any great loss in efficiency.

The Barkhausen oscillator mentioned above is merely typical of the sources that may be used in guides. We have adapted to this work magnetrons such as described by Kilgore[4] and also negative grid tubes such as described by Samuel.[5] In the latter case use has been made of both the fundamental and the harmonic power.

If an oscillator similar to that described above were connected into the middle of a long hollow pipe, waves, would of course, be propagated in both directions. Those that would ordinarily be propagated to the left may be reflected by a suitably located wall or piston so as to reinforce those being propagated to the right. Also an iris of suitable proportions may be so located in front of the generator as to further enhance

oscillations. As has been pointed out, above, the section of pipe bounded by the piston and iris together approximate in behavior a tuned circuit. It is convenient to regard the chamber as a load impedance characteristic of the vacuum tube itself or perhaps it may more properly be regarded as a transformer by which the oscillator is matched to the line. Under certain circumstances it is convenient to use the adjustable iris as a means of controlling the output of the oscillator.

In practice the generator may possibly be built up from an oscillator unit, a piston assembly and an adjustable iris, all of the same diameter of pipe fastened together by exterior metal clamps as shown in Fig. 3 (C). The open end of this generator may be connected to a guide over which transmission is desired or it may be coupled loosely to some nearby laboratory apparatus on which measurements are to be made.

The total length of the chamber and hence the piston setting will, naturally, depend on the frequency to be generated. The relative position

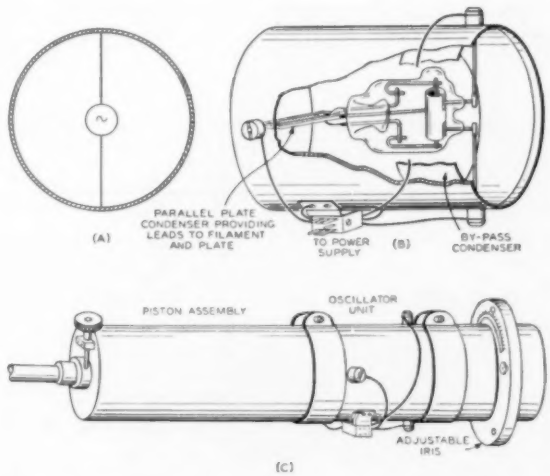

FIG. 3. Various component parts of a wave guide generator (A) Schematic representation; (B) The oscillator unit; (C) Complete generator including oscillator piston and iris.

of the oscillator along the length of the chamber will depend on its impedance characteristics and to some extent on the diameter of the iris opening. However, none of these dimensions is especially critical. For a piece of laboratory apparatus where frequency variability is desired these various dimensions should preferably be adjustable as shown. If a source of single frequency is desired, the resulting apparatus may be greatly simplified as all of these dimensions may be fixed at the time of construction.

The Tuned Receiver

By reversing the principle used in the generator above, replacing the oscillatory source by a suitable detector, the resonant chamber be-

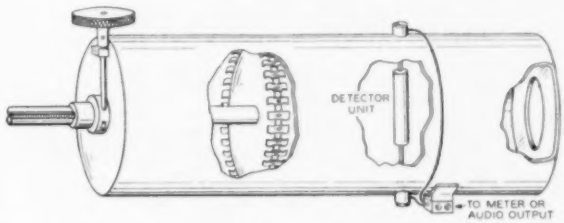

FIG. 4. A tuned receiver based on the resonant cavity principle.

comes effectively a simple tuned receiver. If the detector is appropriately located along the length of the chamber, substantially all of the incident power will be absorbed and the device as a whole will be a veritable sink of wave power. It may be clamped to the end of a long wave guide, thereby constituting a termination, or it may be used to pick up short radio waves of not too small amplitude. See Fig. 4.

In a modification of this tuned receiver in which sharpness of resonance was of greater interest than a maximum of received power, the detector and its mounting were moved to the exterior of the chamber as shown in Fig. 5. Only enough of the resident power was abstracted to operate the indicating meter. This greatly emphasized the resonance effects as might be expected. Under this circumstance it was found that small bits of dielectric introduced into the chamber altered markedly these otherwise sharp resonance effects. This immediately suggested methods for measuring the dielectric properties of materials at these extremely high frequencies.

If the material under investigation is a fluid it may be made to fill the entire chamber. In fact, the earliest experiments done on wave guides

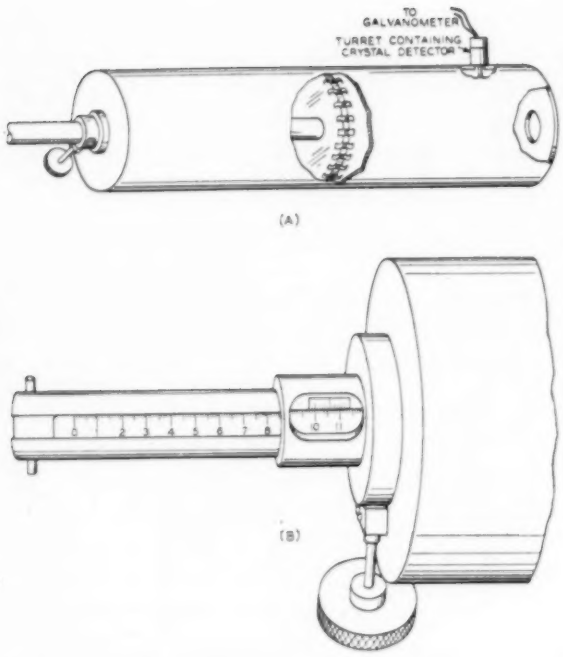

FIG. 5. Form of resonant cavity which may be used either as a wave meter or as means for investigating the properties of certain dielectrics.

were of this kind and used water as the dielectric.[6] They were of such a character that both dielectric constant and absorption index of water could have been determined. It would appear that by this method absorption bands in gases such as the one for ammonia predicted by Dennison[7] and discovered experimentally by Dr. Cleeton and Professor Williams[3] could be located very accurately by such a scheme.

Indicators

It is often desirable to have available in the laboratory some kind of a wave indicator or probe such as shown in Fig. 6. It consists of a simple silicon detector in cartridge form, connected to a nearby microammeter. The former is mounted on a fiber support of convenient size and shape for exploring the fields prevailing around any piece of apparatus. It is easy to show by this means that there are no appreciable fields prevailing around a generator such as described above except near the orifice. Also this probe may be used to determine the approximate orientation of the lines of electric force in the wave front as well as the general directive pattern of the radiation. For the latter purpose it is desirable that the detector be as small as possible and that it not incorporate large amounts of absorbing dielectrics.

The characteristics of the silicon detector are, of course, well known. The one mounted in the resonant chambers shown in Figs. 4 and 5 has already been described.[2] Units may be had that will hold their calibrations moderately well over considerable periods of time. Thermocouples of both the cross wire and deposited type have been used with moderate success. Also diode and triode rectifiers have been tried. However, for general laboratory use where simplicity and convenience are important the crystal detector is perhaps best.

Conclusion

The methods outlined above represent the first steps in a relatively new field of electrical measurements. Work is now in progress directed at measurements of electric intensity and power and accordingly of characteristic impedance and attenuation. The work already accomplished seems to point toward a simplification of measurements that according to the older methods

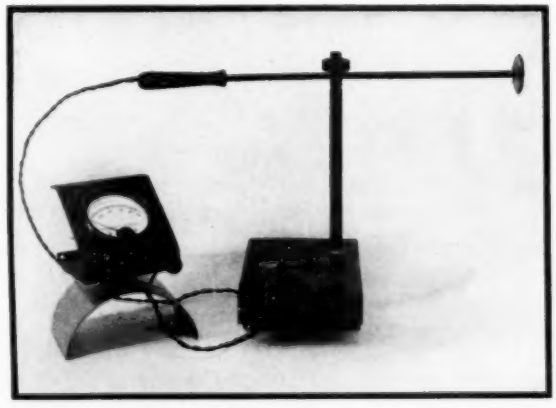

FIG. 6. Simple hand probe for investigating the presence of electric field in and around a wave guide oscillator.

were becoming increasingly more difficult as the frequency was raised. Fig. 7 shows various component parts of a laboratory set-up used for transmitting waves over a wave guide 380 meters in length.

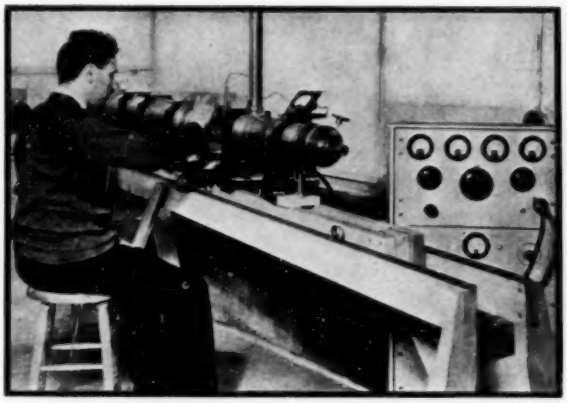

FIG. 7. Transmitting end of an experimental wave guide.

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The relations between academic and industrial research in the physical sciences at the present time, the extent to which progress depends on team work, independent of whether the investigation is prosecuted within the university or within industry, the inspiration and assistance which academic and industrial research in these fields are continually bringing to one another, give fundamental research in the physical sciences special claims upon the support of industry, apart from the rapidity with which discoveries in this field are applied to industrial purposes.

"Science, Industry and Society," *Nature, March 27, 1937*

The Magnetron as a High Frequency Generator*

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I. Introduction

THE search for methods of generating ultra-high frequencies has followed two main paths. One has been the improvement of the negative grid tube as an oscillator and amplifier so as to extend its upper frequency limit. The other has been the investigation of less conventional vacuum tubes that appear to be applicable at high frequencies. Of the latter group the magnetron now stands out as one of the most promising tubes.

The device first called a "magnetron" by Hull[2] in 1921 is well known as a vacuum tube having a cylindrical plate structure and coaxial filament, with a uniform magnetic field directed along the electrode axis. Its use as a generator of high frequency currents has developed mainly in the past decade and its investigation has claimed the attention of a large number of research workers in many countries.

Magnetrons in a variety of structural forms and in a number of operating modes have been used for oscillation generation. Broadly speaking, magnetron oscillators can be divided into two classes; one using an alternating magnetic field, and the other using a constant magnetic field. The alternating-field type described by Elder,[3] in which the field coil is part of the oscillating circuit, is obviously limited to low frequencies and need not be considered in the present discussion. The constant field types which are useful in generating ultra-high frequencies can be subdivided as negative resistance oscillators and transit time oscillators.

The negative resistance magnetron oscillator may be defined as one which operates by reason of a static negative resistance between its electrodes and in which the frequency is equal to the natural period of the circuit. In Europe this type is sometimes called "dynatron magnetron" or Habann oscillator.

The transit time magnetron oscillator may be defined as one which operates by reason of electron transit time phenomena and in which the frequency is determined by the electron transit time. This type is often referred to as an "electronic oscillator" and sometimes as a "magnetostatic oscillator."

It is the purpose of the present paper to survey the various types of magnetron generators with particular reference to their performance and limitations at ultra-high frequencies.

II. Negative Resistance Magnetrons

In reviewing magnetron oscillators, it is well to begin with the negative resistance magnetron since its operation is more nearly like that of conventional tubes. Historically, the basic idea of the negative resistance magnetron was disclosed by Habann[4] in 1924, and the common push-pull arrangement of the split-plate magnetron was introduced by Manns[6] in 1927. Since that time a number of papers on the application of this device to the generation of ultra-high frequencies have appeared.[11, 13, 18, 20]

The tube in its usual form consists of two semicylindrical plates with a co-axial filament and is operated in a circuit as shown in Fig. 1. In order to start oscillations the magnetic field directed

* Presented at the Madison, Wisconsin meeting of the American Physical Society, June 22–23, 1937.

along the axis of the tube must be increased to a value slightly above the critical value[1]

$$H_{cr} = 6.72 E_p^{\frac{1}{2}} / r_p \text{ gauss},$$

where E_p = plate potential in volts,
r_p = plate radius in centimeters,

under which condition the electrons miss the plate on their first passage. After oscillations are started, the magnetic field can be increased to a much higher value and its adjustment is not particularly critical.

The reason for oscillation can be explained on the basis of a static negative resistance characteristic of the type shown in Fig. 2. This characteristic is obtained by measuring the current to the plate halves as the potential on one is increased by increments and the potential on the other is decreased by the same increments, so as to simulate conditions during oscillation. It can be seen from this curve that at first more current flows to the plate at lower potential and that, as the difference of potential $(E_A - E_B)$ is increased, the excess of current to plate B increases, resulting in the negative resistance curve OP. If this negative resistance is low enough, self-sustained oscillations can be produced in a tank circuit connected across the two plates.

A good physical picture as to the reason for the negative resistance characteristic can be found by turning briefly to a study of electron paths. Figs. 3*a*, 3*b*, 3*c* illustrate typical electron paths which were estimated from the electrostatic and magnetic fields. Fig. 3*a* shows the case of equal potentials on the plate halves under which condition the electrons travel in symmetrical paths, very few reaching either plate. When the plate halves are at different potentials, the electrons describe more complicated paths, usually landing

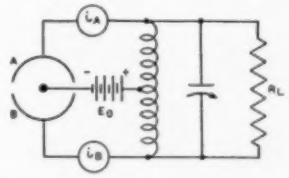

FIG. 1. Two-segment magnetron oscillator circuit.

on the plate at lower potential, either as shown in Fig. 3*b* or Fig. 3*c*. In these examples the magnetic field is approximately 1.5 times the critical value. Electron paths of this type have been clearly demonstrated in a special gas-filled beam magnetron which makes the beam trace visible by ionization.[30] A photograph of a beam trace of this type is shown in Fig. 3*d*.

The static curves shown in Fig. 2 can be used to calculate power output, efficiency and load

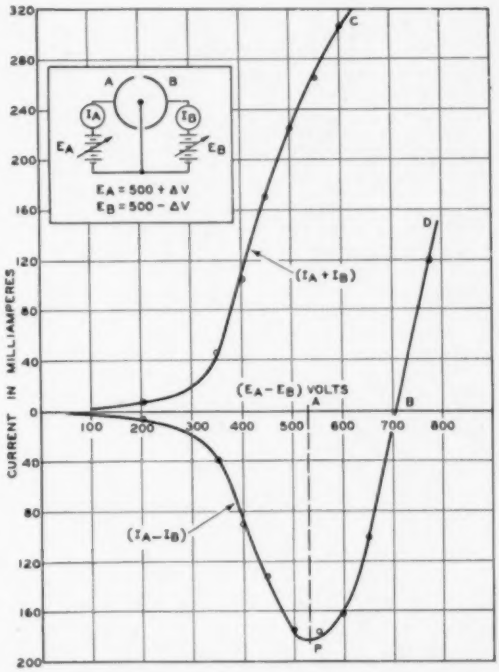

FIG. 2. Static characteristics of a two-segment magnetron showing negative resistance.

resistance. From computations of this sort which have been made by several investigators,[13, 30] it can be concluded that at low frequencies an efficiency comparable to that of the feed-back oscillator is to be expected, and that the load impedance required for optimum output is somewhat higher.

Performance at High Frequencies

Although the high efficiency predicted from the static characteristics can be demonstrated at low and medium frequencies, it is found on going to very high frequencies that the efficiency decreases much in the same manner as for the negative grid oscillator. Typical curves of efficiency *versus* frequency are shown in Fig. 4. This decrease in efficiency was first ascribed mainly to circuit losses, but later it was demonstrated that even with circuits of negligible loss the efficiency still decreased at extreme frequencies, and in a manner to suggest electron transit time effects.

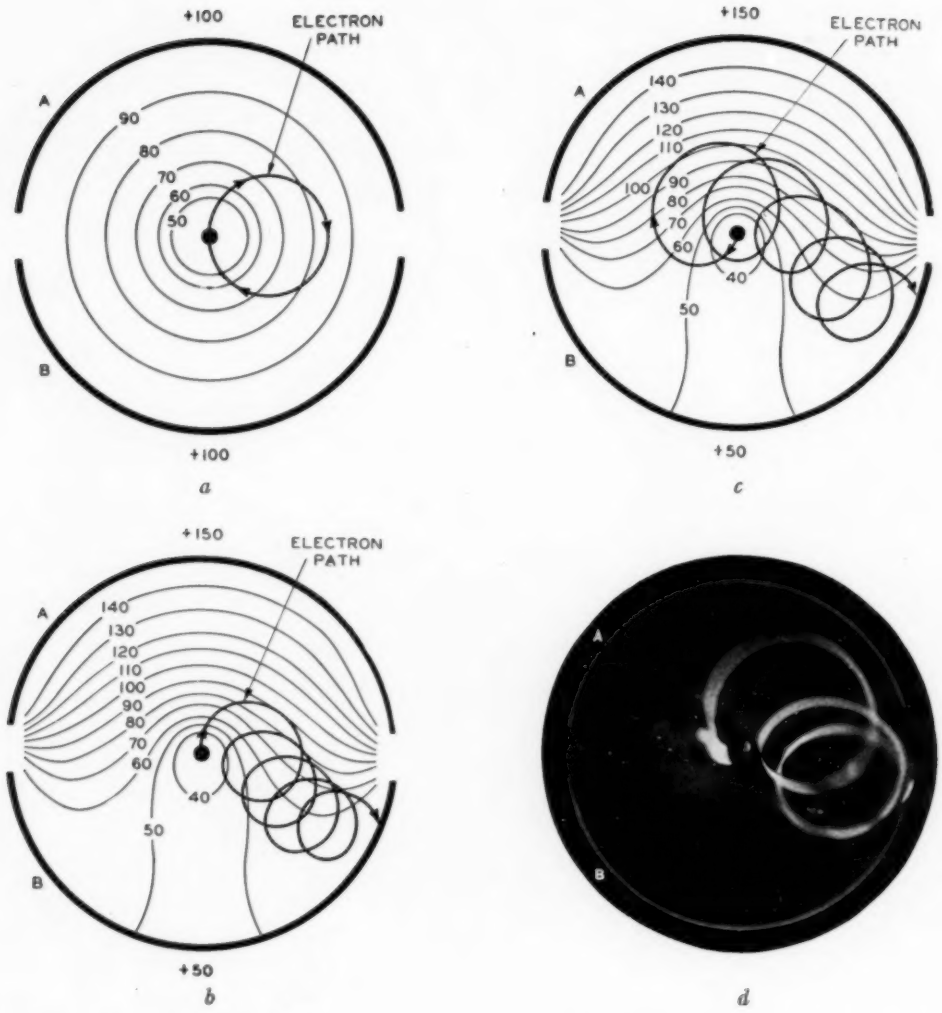

FIG. 3. Typical electron paths in a two-segment magnetron, showing how electrons arrive at the plate-half of lower potential.

This point is made clear by Fig. 5 where efficiency data are plotted against the ratio of electron transit time to period, for several tubes of various plate diameters and plate voltages. The transit time figure used is somewhat arbitrary, being approximately one-half the time required for an electron to describe a complete orbit. It is numerically equal to $2.65\times10^{-8}\, r_p/(E_0)^{\frac{1}{2}}$ seconds. The fact that all these data fall quite close to a smooth curve is evidence that the decrease in efficiency is due to transit time effects.

These data from the author's paper[30] show the same general trend of efficiency, as found by most of the other workers in the field. For example, Fig. 6 shows a curve taken from a paper by Herriger and Hulster.[27] Here efficiency is plotted against a factor which the Germans term the "order" of oscillation. This is the number of electron orbits described per period, or one-half the reciprocal of the abscissa of the previous curve. These data, when compared on the same basis, agree fairly well with that of the author. Megaw,[29] however, in a recent paper states that the efficiency increases in the intermediate region just before the limiting frequency is reached. He accounts for this by transit time effects but does not show any experimental data to substantiate his statements.

The general efficiency curve of the type shown in Fig. 5 is very useful in predicting performance. It shows that for reasonably high efficiency, the transit time must be one-tenth period or less. This

means that for high efficiency at high frequencies either high plate voltage or small plate diameter must be used. For example, to obtain 40 percent efficiency at 50 cm wave-length with a plate diameter of 0.5 cm, a plate potential of 1600 volts is required.

In addition to these requirements, it can be shown that a high magnetic field is required, since the magnetic field strength is connected with transit time in a more fundamental way than either plate voltage or plate diameter. This follows directly from the fact that the orbital time of an electron is nearly inversely proportional to the magnetic field strength. This reveals the important fact that for a given frequency and efficiency the value of magnetic field required is determined regardless of what plate voltage or plate diameter is used. As an example, for 30 percent efficiency at 50 cm wave-length, a field strength of approximately 1600 gauss is required, while for the same efficiency at 5 cm wave-length, 16,000 gauss would be required. The field strength required is clearly a serious factor in applying the negative resistance magnetron to extreme frequencies.

Circuit Limitations

In the foregoing work the circuit limitations were for the time neglected. However, the circuit problem is important in the negative resistance magnetron as well as in the negative grid oscillator, particularly when an attempt is made to obtain very short wave-lengths. The circuit appears as a limitation in two ways; first, the size of circuit becomes so small as to allow little or no circuit external to the tube; and second, the circuit losses increase with frequency and thus decrease overall efficiency.

At wave-lengths around 50 cm, it becomes necessary to mount the whole oscillating circuit within the tube envelope. An illustration of this is shown in Figs. 7 and 8. The internal circuit is inductively coupled to the load through a loop not shown.

The importance of low loss, high impedance circuits is seen when it is considered that for the usual negative resistance magnetron the optimum load impedance calculated from static curves is from 5000 to 10,000 ohms. This means that in order to keep the circuit loss down to a reasonable value, circuit impedances of 25,000 to 50,000 ohms must be used.

The circuit losses are largely due to skin effect and radiation. The first can be minimized by using conductors of low resistivity material having fairly large surfaces. The second can be

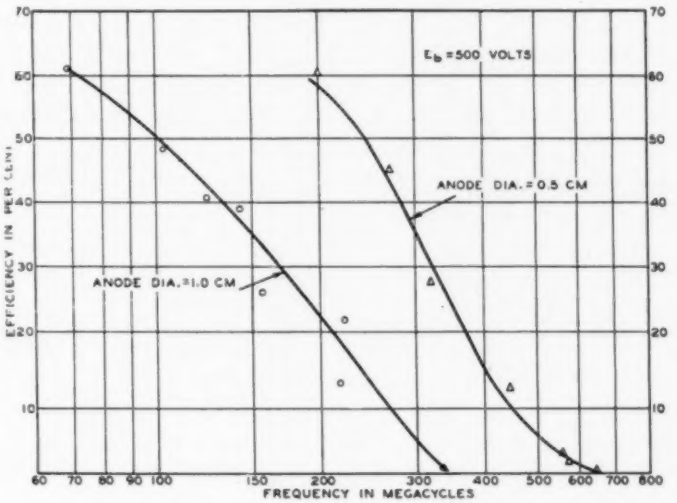

FIG. 4. Efficiency of a two-segment magnetron as a function of frequency.

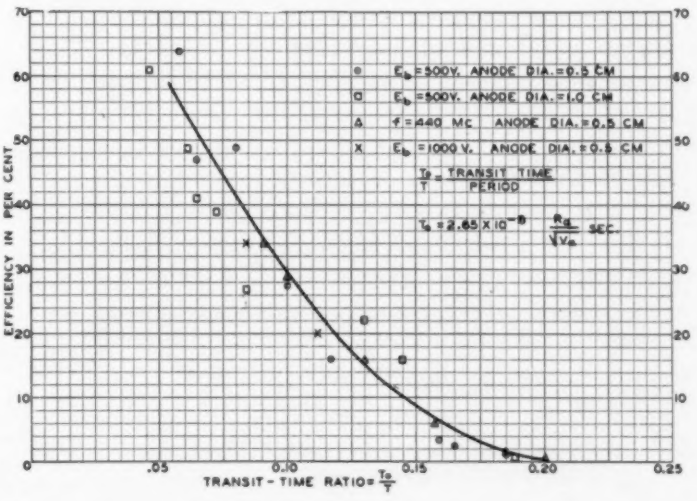
E_b =500V. ANODE DIA.=0.5 CM
E_b =500V. ANODE DIA.=1.0 CM
f =440 MC ANODE DIA.=0.5 CM
E_b =1000 V. ANODE DIA.=0.5 CM
$\frac{T_o}{T}$ = TRANSIT TIME / PERIOD
$T_o = 2.65 \times 10^{-9} \frac{R_a}{\sqrt{V_a}}$ SEC.
EFFICIENCY IN PER CENT
TRANSIT-TIME RATIO = $\frac{T_o}{T}$

FIG. 5. General efficiency curve of two-segment magnetrons as a function of the ratio of electron transit time to period.

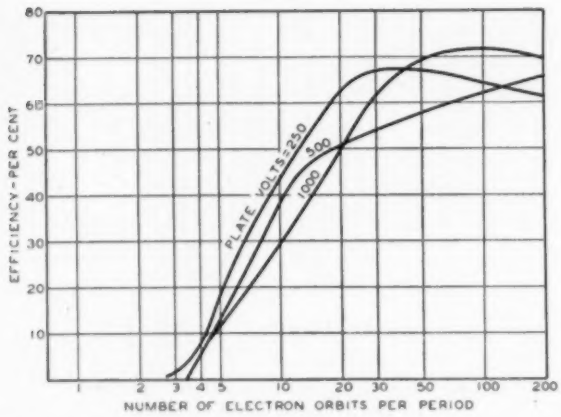

FIG. 6. Efficiency curves of a two-segment magnetron as a function of the number of electron orbits per period. From the paper by Herriger and Hulster.

minimized by using close spacing of the leads (of the order of 1/100 wave-length). However, to secure optimum design of circuit for a given tube capacity, there must be a compromise between the two losses since decreasing the conductor spacing beyond a certain point increases the conductor loss.

As to practical cases, little data are yet available, but it is safe to say that circuit impedances as high as 25,000 ohms can be obtained at wave-lengths as short as 50 cm. But, as the frequency is increased, the problem becomes more serious due to the fact that if circuit dimensions are decreased in proportion to wave-length the impedance decreases as the square root of the wave-length.

There is one compensating factor, however, in that there is apparently some decrease in dynamic impedance of the tube at the higher frequencies where transit time effects come into play.[29]

Output Limitations

The requirements of high plate voltage and small anode size for high efficiency both make for high plate dissipation per unit area. Plate dissipation therefore becomes one of the most serious factors in limiting output of the negative resistance magnetron at high frequencies.

Some progress has been made in the way of increasing dissipation limit and output by using a heavy walled plate structure to increase the radiation surface. Still further increase in dissipation has been obtained by placing the oscillating circuit within the tube envelope as shown in Fig. 7. The conductors being of large cross section and of good thermal conductivity, the whole circuit serves to dissipate heat. By this means the effective radiation surface can be increased by a factor of about 20 to 1. A tube of this type built in the RCA Radiotron Laboratory is shown in Fig. 8 which will deliver approximately 50 watts output at a wave-length of 55 cm.[30]

Still larger increase in output has been obtained by water cooling the plate surface. One type of water cooled tube is shown in Fig. 9. A tube of this construction gave a useful output of approximately 100 watts at a wave-length of 50 cm.[30]

Another effective means of water cooling described by Pfetscher and Puhlmann[28] of the University of Jena is shown in Fig. 10. The water cooling combined with continuous exhaust allowed these tubes to be operated at voltages several times higher than normally used, with a consequent increase in output. One tube of the type shown in Fig. 10b gave an output of 450 watts at a wave-length of 46 cm, and a smaller tube gave 80 watts output at 19 cm. This represents the best performance reported so far for negative resistance magnetrons and is far above the outputs obtainable at these wave-lengths by any other means.

III. Transit Time Magnetrons

The second class of magnetrons for generating ultra-high frequencies as defined above is characterized by the fact that the frequency is determined by the electron transit time. Oscillators of this type are of importance because they are capable of generating currents at extremely short waves.

The first record in the literature of transit time magnetrons is that of Zacek[5] who in 1924 dis-

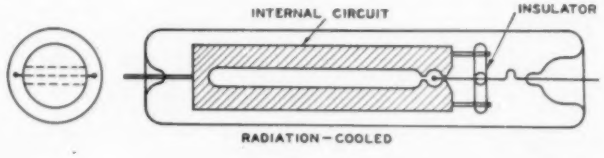

Fig. 7. Sectional view of an internal circuit radiation cooled magnetron for obtaining high power at ultra-short waves.

covered oscillations in a cylindrical diode. Not much importance was attached to this kind of generator until Okabe[7] in 1928 showed that a much larger output could be obtained by a split-plate construction such as had already been used by Habann and Manns for negative resistance oscillators. Okabe expressed the empirical relation that the wave-length

$$\lambda = 12{,}000/H_{\text{gauss}} \text{ centimeters},$$

which corresponds to the condition that the period of oscillation is approximately equal to the orbital time of the electron.

The plate construction and circuit arrangement are usually the same as for the negative resistance magnetron. The operating conditions, however, are somewhat different. The magnetic field must not only be adjusted near critical but must also be at a particular value for a given wave-length. This means that plate voltage and field strength are both critical in adjustment. In addition, it has been found that the magnetic field must be inclined at an angle of a few degrees to the tube axis.[9, 10, 12]

The basic mechanism of this type of oscillator is best explained by considering two groups of electrons; one which absorbs energy from the circuit, and the other which delivers energy to the circuit. The loss electrons are those reaching the slot field just in time to be given an accelerating impulse which will in general cause them to be absorbed by the plate with a resulting energy loss.

The useful electrons are those reaching the slot field in the proper time to be decelerated. These electrons give up an increment of energy and thereby miss the plate, describing several orbits, each time reaching the slot region in proper phase to give up energy, the orbital time being equal to one period. Under proper conditions the net effect is that more energy is given up to the circuit by the useful group than is absorbed by the loss group, and thus self-sustained oscillations can exist.

The tilting of the field is apparently necessary in order to draw the electrons out of the electrode space before they make too many trips, which would result in an excess space charge, and in turn would effect the orbital time, causing the electrons to get out of phase. It is also probable that the orbital time of an electron differs slightly on successive orbits so that in general an electron cannot make very many orbits before getting out of phase. It is therefore desirable to withdraw an electron before it gets out of phase and results in energy absorption.

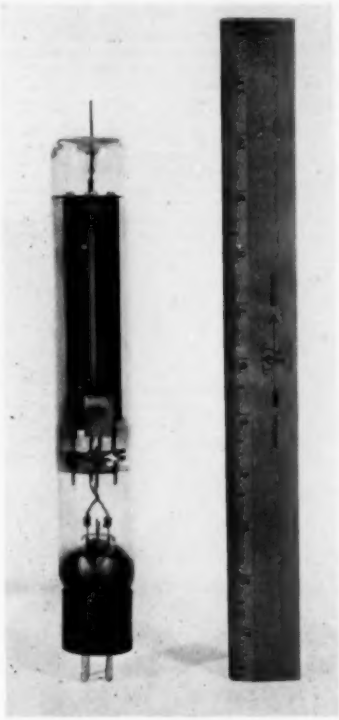

FIG. 8. Photograph of an internal circuit radiation cooled magnetron for a wave-length of 55 cm.

Unlike the negative resistance magnetron, the transit time tube is very critical to filament emission and requires a much smaller emission for optimum output. Usually, the optimum plate

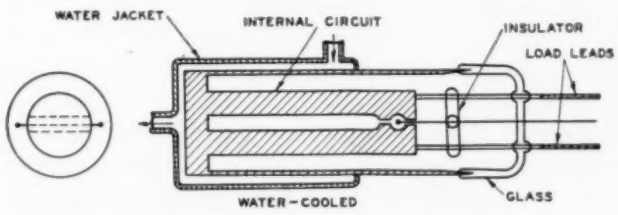

FIG. 9. Sectional view of one type of water cooled magnetron for ultra-short waves.

current is reached before the plate dissipation limit occurs.

It has been found experimentally that a given tube can deliver appreciable output only over a

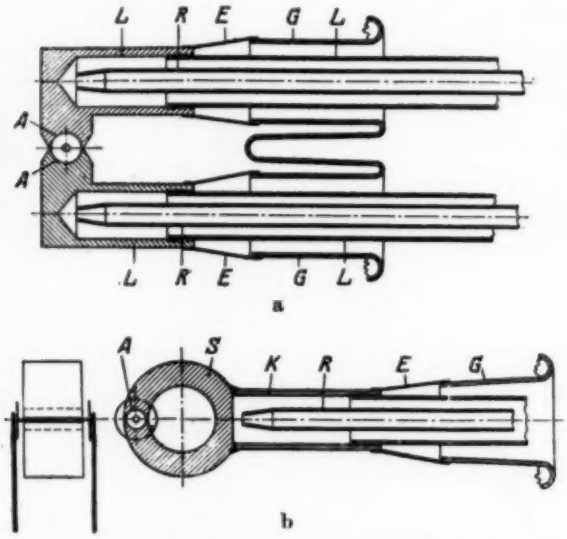

FIG. 10. Sectional view of two types of water cooled magnetrons described by Pfetscher and Puhlmann.

limited range of frequency. The output drops at the lower frequencies because of reduced voltage required and is limited at the high frequency end due to a type of instability called "filament bombardment" which will be discussed later. Empirical relations useful in design of these tubes are that the optimum anode diameter is about 1/20 of the wave-length, and the useful frequency range is approximately 2 to 1. To cover a wide range of frequencies with the transit time magnetron, a large number of tubes of different sizes must be used.

The usual efficiency obtained with the 2-plate transit time magnetron is around 10 percent, while for the diode type it is about 1 percent.[12] The output obtainable is a function of the wave-length, varying from about 10 watts at 50 cm, to 1 or 2 watts at 10 cm.

The diode magnetron has not been commonly used because of its extremely low efficiency. However, C. W. Rice[33] of the General Electric Laboratories has recently described a diode magnetron giving several watts output at 5 cm wave-length. The comparatively large output is obtained by using a water cooled tube with several hundred watts input.

An interesting feature of the transit time magnetron is that due to its basic mechanism it can be operated into a much lower impedance load than the negative resistance magnetron, and so does not require a circuit of such high impedance. This comes about from the fact that a small amplitude of potential on the plate halves can give rise to a large circulating electron current which in an ordinary tube would require much higher voltage amplitude. Experimentally, it has been found that transit time magnetrons will work into a load resistance of the order of one-tenth that of the negative resistance magnetron and that oscillations can be sustained in circuits with an impedance of the order of 100 ohms. This is one reason why it has been possible to operate these tubes at such extreme frequencies where the circuits are unquestionably very poor.

Another factor in favor of the transit time generator is that it requires a much smaller magnetic field for a given frequency. This follows directly from the fact that in negative resistance oscillators the electron transit time must be a

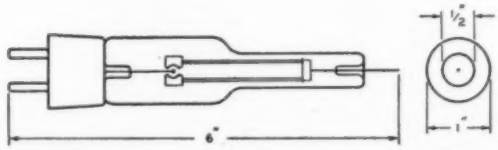

FIG. 11. Early type of internal circuit transit time magnetron for generating 9 cm waves (Westinghouse Electric and Manufacturing Co.).

much smaller fraction of the period than in the transit time type. The transit time for the latter type is of course one-half period while for the negative resistance type operating at the same efficiency it must be less than one-eighth period (see Fig. 5). The negative resistance magnetron, therefore, requires approximately four times the field strength for a given frequency.

Improved Types

Since the advent of the split-plate construction, two major improvements in transit time magnetrons have been made; namely, the use of an internal circuit construction for obtaining extremely high frequencies, and the use of the end-plate construction.

In 1932, transit time magnetrons of the internal circuit type were built in the Westinghouse Laboratories[15] for the generation of 9 cm waves.

An early tube of this type is shown in Fig. 11. In this tube the circuit is slightly more than one-half wave-length long. The shorting bridge is at the second voltage node, the first node occurring less than a millimeter from the plate. The circuit is coupled inductively to the load. Still smaller tubes with internal-circuit constructions have been described by Williams and Cleeton.[17, 22, 34] These tubes were used to generate high frequency currents at wave-lengths as short as 6 millimeters.

The second improvement came with the end-plate magnetron disclosed by Linder[20] of the RCA Victor Laboratories. This tube is similar to the split-plate magnetron except that two electrodes are added at the end of the plate cylinder. These end plates are maintained at a positive potential slightly lower than that of the split plates. The construction of the end-plate magnetron is clearly shown in Fig. 12. In this tube an internal circuit is used with a shorting bridge placed at the first voltage node, with a transmission line brought out to the load.

Linder[25] has shown that end plates serve the same purpose as tilting the magnetic field, in removing electrons from the interelectrode space after they have made several orbits. He has found that the end-plate tube gives somewhat higher output and efficiency than the simple split-plate tube and that it is easier to stabilize. He has reported an output of 2.5 watts and 12 percent efficiency at a wave-length of 9 cm, as compared to about 1 watt and 8 percent efficiency obtained from tubes without end plates.

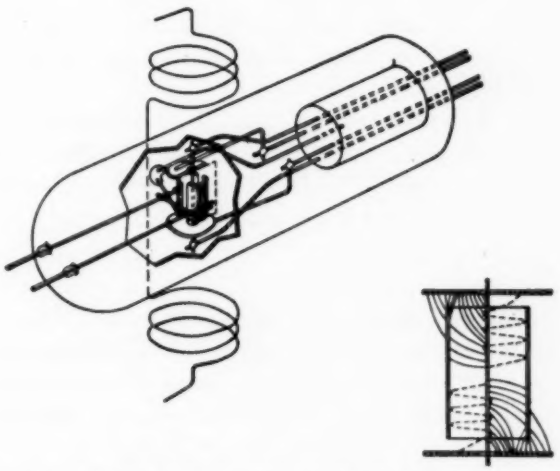

FIG. 12. End-plate magnetron showing internal circuit and transmission line.

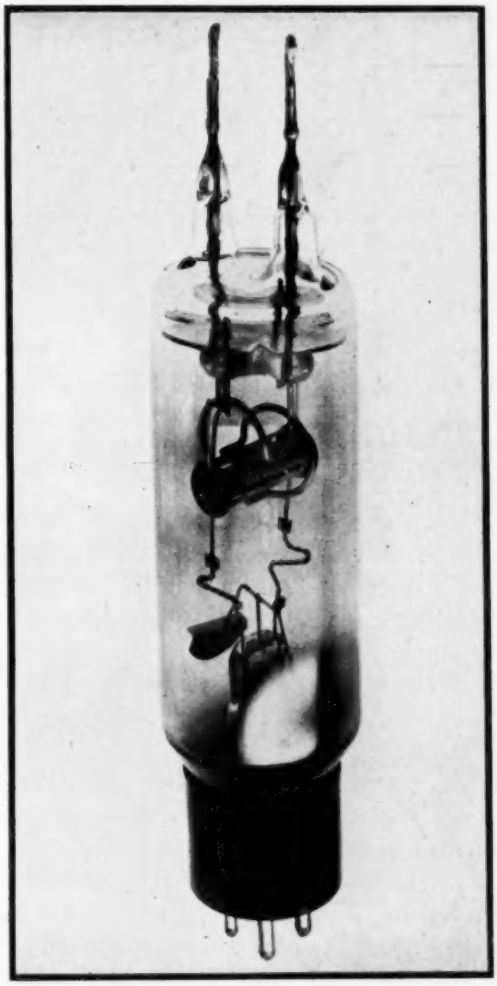

FIG. 13. Four-segment magnetron with internally connected segments.

Multi-Segment Tubes

A survey of magnetrons would not be complete without some mention of tubes having more than two segments, particularly the four-segment construction. A four-segment tube was described in the literature as early as 1928 by Yagi.[8] In the past few years considerable attention has been given to this tube, particularly in Europe.[21, 27] In the common construction of these tubes, opposite pairs of plates are connected together and only a single pair of leads is brought out as shown in Fig. 13. There appears to be considerable controversy both as to the theory of operation and to the actual performance of these tubes.

The four-segment tube, like the two-plate tube, has static negative resistance, but as it is norm-

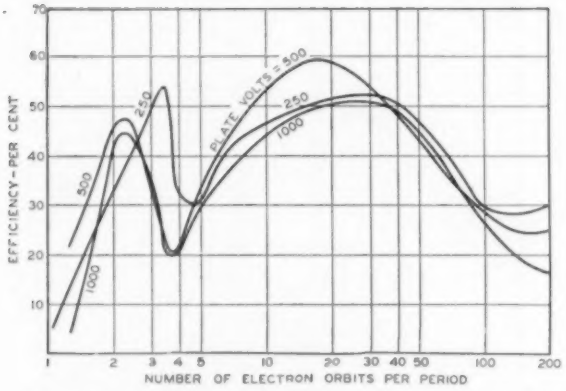

FIG. 14. Efficiency curves of a four-segment magnetron as a function of the number of electron orbits per period. From the paper by Herriger and Hulster.

ally used, the operation appears to be more like a transit time oscillator in that the frequency is critically related to the period. The output and efficiencies are usually intermediate between that of the negative resistance mode and the transit time mode of the two-plate construction, although some writers have reported very high efficiencies.

Herriger and Hulster[27] have published the most extensive experimental data on the four-plate tube. Fig. 14 shows their curve of efficiency *versus* electron orbits per period similar to that shown for the two-plate tube. The first maximum near the "order" two represents the usual operation condition for the tube, in which case the tube appears to be operating in the transit time mode. Where the number of orbits per period is very large, the oscillations can probably be explained on the basis of static negative resistance. It is interesting to note that for usual operating conditions the field strength required is approximately one-half that required by a two-plate tube operating in the negative resistance mode at the same wave-length.

In general, it can be said about the four-plate tubes that in the present state of development they are not capable of generating any shorter wave-length or higher power than can be obtained with the simpler two-plate construction. However, the high efficiencies reported are encouraging and it is probable that this tube will find a useful application in generating frequencies intermediate between the two-plate transit time oscillator and the two-plate negative resistance oscillator.

IV. Miscellaneous Problems

In presenting a fair picture of the present status of the magnetron oscillators, it is necessary to consider several factors which tend to limit their successful operation and useful application. These factors can be listed as follows:

(1) Filament bombardment
(2) Modulation
(3) Frequency stability
(4) Magnet requirements

The filament bombardment effect has been reported by a number of the magnetron investigators[14, 16, 25, 30] and is generally regarded as one of the most serious limiting factors, particularly in negative resistance magnetrons, when attempts are made to obtain very high power. This phenomenon exhibits itself by an increased heating of the filament which results in an unstable condition and a shortening of the life of the tube. Several good papers on this effect have appeared recently in the journals of the U.S.S.R.[31, 32] A rather complete investigation of this problem has also been made by Linder.* There are a number of opinions as to the physical nature of this effect and the question is still unsettled. However, it has been shown rather conclusively that the effect can exist with or without oscillations and that it is due to bombardment of the cathode by charged particles either positive ions, electrons, or both. Although this problem now appears as a serious limiting factor, there seems to be some hope for its solution. Megaw[29] and Ladner[24] have proposed the use of an auxiliary electrode for protecting the filament, and others are attempting filament stabilization methods.

The practical utilization of any high frequency generator for communication purposes depends upon the possibility of its being modulated. The magnetron in both its forms offers certain problems in modulation that are not present in conventional oscillators. The oscillation voltage of the negative resistance magnetron is a nonlinear function of the plate voltage, often being discontinuous at some points. This makes it impossible to use simple plate voltage modulation. Transit

* E. G. Linder, "Excess energy electrons and electron motion in high vacuum tubes." Paper submitted to the Institute of Radio Engineers for publication.

time tubes do not exhibit this difficulty but they do show appreciable frequency change with plate voltage. These problems will require further research before they are completely solved, but already considerable progress has been made.

Von Lindern[23] has described a method of modulating magnetrons in which the carrier amplitude remains constant but is keyed on and off at an intermediate frequency. Modulation is obtained by varying the portion of the intermediate frequency period during which the carrier is on. Another interesting method reported by Linder and Wolff[19] is the use of an ionized gas modulator which modulates the radiated output from a beam transmitter. Modulation by means of an auxiliary electrode has been investigated by Groszkowski and Ryzko[26] and others.

The frequency stability of the present magnetrons leaves something to be desired, but it does not appear that the negative resistance type at least is inherently more unstable than a negative grid oscillator. The transit time oscillator which depends upon electron transit time requires extremely well-regulated voltages and a very constant magnetic field. Recently, Megaw[29] has reported frequency stability with a transit time magnetron sufficient to give an audible beat note between two oscillators operating above 1000 Mc.

The magnetic field power and size of electromagnet are often used as objections to magnetron generators. However, with magnet steels now available permanent magnets can be used for many applications where the power in the magnet is a limitation; and by proper design, the size of electromagnets can be made small compared to the whole equipment except at extremely high frequencies. An illustration of the relatively small size of magnet required for the 9 cm endplate magnetron can be had from Fig. 15 which shows a 9 cm beam transmitter.[20]

V. Conclusions

To sum up the present status of magnetron oscillators the following statement can be made: In one mode of operation where the oscillations depend on a static negative resistance, the magnetron offers a means of generating larger amounts of power at wave-lengths below 100 cm than can be generated by any other type of vacuum-tube generator at the present time. In another mode where the oscillation mechanism depends upon electron transit time, the magnetron offers a means of generating the shortest continuous radio waves.

The negative resistance magnetron is particularly useful in the range of wave-lengths extending roughly from 100 cm to 30 cm. Radiation cooled tubes of this type are capable of generating power of the order of 50 watts at a wave-length of 50 cm, and special water cooled tubes can deliver more than 100 watts output, at the same wave-length.

The transit time magnetron is useful in generating high frequency currents at wave-lengths below 30 cm. Power outputs of a few watts can be generated at wave-lengths around 10 cm and detectable currents can be generated at wave-lengths as short as a few millimeters.

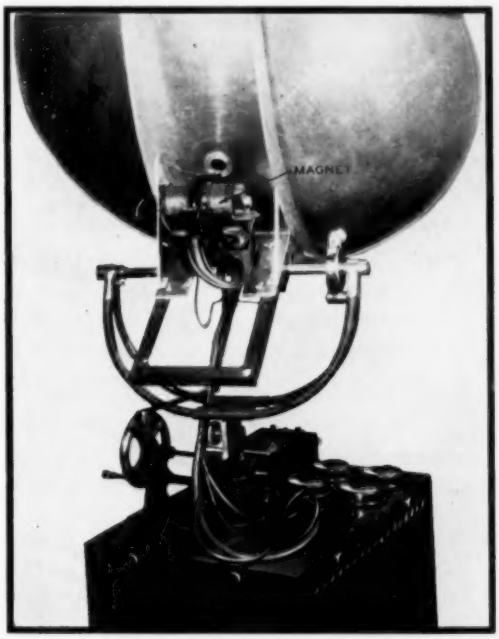

FIG. 15. 9 cm magnetron beam transmitter showing relatively small size of electromagnet.

In spite of certain factors that at present tend to limit the operation of the magnetron, it has already proved to be a useful tool in the exploration of the ultra-high frequency region. With the active development which this type of generator is undergoing, it may be expected to find many practical uses in the future.

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Extending the Frequency Range of the Negative Grid Tube*

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WITH the advent of any new discovery the research worker is inclined to discard old principles and old practices as being unworthy of further consideration. On sober after-thought it sometimes appears that the full possibilities of the old ideas have not been explored. Such perhaps, has been the case in the matter of ultra-high frequency oscillation generators. It may be of interest therefore, to reconsider the conventional negative grid vacuum tube and find out just what it can do in competition with certain newcomers, in this field.

My purpose in discussing this matter with you is twofold. In the first place I think that you, as physicists, will be interested in some of the fundamental limitations which appear at ultra-high frequencies. Then, in addition, you may be interested in knowing something about the tools that are available for research at these frequencies. The negative grid tube offers interesting possibilities in this field.

It might be well to enumerate some of the more outstanding advantages of the negative grid tube as compared with the Barkhausen and magnetron tubes. The negative grid tube's greater usefulness comes about because of its ability to amplify, a property of greatest value in the communication industry and one not possessed by either the magnetron or the Barkhausen oscillator. It is also easy to modulate, again a property useful in communication. An advantage of more general interest is the possibility of precise frequency control. Then, of course, there is the long background of experience in the use of such devices, and the availability of standard accessory equipment which must be reckoned with.

But, you may ask, why should one consider the vacuum tube as being any different at high frequencies than it is at low, and why cannot the conventional tubes be used in this frequency range: to which I will reply, that some special concepts are required to understand the behavior of vacuum tubes at the frequencies under consideration, and that these concepts at once show why the conventional design of radio tube fails to operate.

To the physicist there is nothing very profound or new about these concepts. One has to do with the finite time required by the electrons in their passage between the electrodes of the tube, the so-called electron transit time; the second concept relates to the increased importance at high frequencies of the electrostatic capacitances existing between the tube electrodes and to the inductance of the leads which connect these elements to the terminals outside the tube envelope. In fact, the simplified concepts of inductance and capacitance themselves need modification at frequencies for which the dimensions of the tube structure and its supporting leads become at all comparable to the operating wavelength. But even this is far from new.

What may be new to you is the unexpected and sometimes devious ways in which these factors affect the performance of the vacuum tube at high frequencies. Also of interest may be

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the unconventional appearing structures which have been adopted to circumvent the restrictions imposed by the high frequency operation.

Now to consider this problem of transit time. The problem of calculating the electron transit time in complicated tube structures is of itself a difficult problem. The quantitative analysis of its effect is even more complicated.[1] For our present purpose we will note that because of its finite nature the action of the tube cannot be instantaneous. A sinusoidal potential applied to the control grid will not produce an in-phase component in the output current. The calculation of this delay is complicated by an important distinction which must be drawn between the rate of arrival of electrons at any electrode and the current to that electrode. While the role played by the displacement components of current can only be evaluated by mathematical analysis, some insight into the problem may be gained by considering the component of current to a given electrode associated with the passage of a single electron between the cathode and anode of a simple three element tube. When the electron leaves the cathode it may be considered as introducing image charges in the cathode, control element, and anode. The components of current required to redistribute these image charges, as the electron moves, actually constitutes the electrode currents. Viewed in this light the components of current associated with the electron begin to exist when that electron leaves the cathode and cease to exist when the electron arrives at the anode. The electron is, of course, continuously acted on by the varying electrostatic field resulting from potentials applied to the anode and the control electrode, and it is continuously contributing to the electrode currents. The net effect of this state of affairs is to produce a phase lag, but one not commensurate in magnitude with the total transit time. Difficulties in compensating for this delay result in lower efficiencies of operation.

Since the electron by its motion contributes to the electrode currents, the current which it contributes in any given electrode bears very little relationship to the actual arrival of the electron at the electrode. Currents of considerable magnitude may exist in a control electrode even though the electrons are not allowed to strike this element. The phase relationship of such currents will depend upon the exact time in the alternating cycle at which the electron leaves the cathode and upon the relationship between the transit time and the period of the applied potentials. Under the usual conditions the net flow of energy will be from the source supplying the control electrode potential to the electron stream. The electrons will, on the average, arrive at the anode with velocities corresponding to potentials

TABLE I. *The effect of a 20 percent reduction in wave-length and in linear dimensions of the tube structure.*

	Dimensional Equivalent	Assumption		
		$V=C$	$I/A=C$	$P/A=C$
Wave-length	λ	20%	20%	20%
Linear dimensions	1	20	20	20
Electrode potentials	V	100	12	28
Amplification factor	—	100	100	100
Interelectrode capacitances	1	20	20	20
Lead inductances	1	20	20	20
Circuit impedances	$1\lambda^{-1}$	100	100	100
Plate current	$V^{3/2}$	100	4	14
Trans-conductance	$V^{1/2}$	100	34	53
Electron transit time	$V^{-1/2}1$	20	57	38
Input resistance	$V^{1/2}1^{-2}\lambda^2$	100	34	53
Required emission density*	$V^{3/2}1^{-2}$	2500	100	360
Required dissipation density	$V^{5/2}1^{-2}$	2500	12	100
Power output	$V^{5/2}$	100	0.5	4

* Neglecting charging current component.

greater than the potential of the anode at the instant of their arrival. The excess energy is dissipated in the form of heat and decreases the useful output of the tube. The contributions to this energy supplied by the control grid are commonly referred to as the "active grid loss" since they occur only under active conditions, that is, with a high frequency potential on the grid. A number of workers have dealt with this problem both mathematically and experimentally.[1] The resulting input resistance has been found to vary inversely as the square of the ratio of the transit time to period. Some references to actual values will be mentioned later.

The large displacement currents which exist at ultra-high frequencies increase the emission demands placed on the cathode of the tube. At low frequencies the rate at which electrons leaves the cathode at any instant is substantially identical with the rate at which they arrive at the anode. At high frequencies this is no longer true. Consider a simple two element tube operating under conditions of complete space charge, which means that the potential gradient at the cathode must always be zero. Since no displacement currents can flow at this point, and since the total current in a closed circuit at any instant must be the same at all points, the instantaneous electron emission from the cathode must be equal to the instantaneous sum of the displacement and conduction components of current at the anode. In the triode or multielement tube the problem is complicated by the presence of parallel circuits but the same principle holds.

The second concept, as I have said, relates to the tube as a circuit element. In the first place a limiting frequency of operation is set by the resonant circuit formed by certain of the tube interelectrode capacitances and lead inductances; but even before this frequency limit is reached, difficulties are encountered in an amplifier because of interaction between the input and output circuits. Such interaction or "singing" becomes extremely difficult to control at ultra high frequencies. The large charging currents to the interelectrode capacitances which must occur in the tube leads cause excessive energy losses with a consequent loss in efficiency. In some cases the heat liberated actually endangered

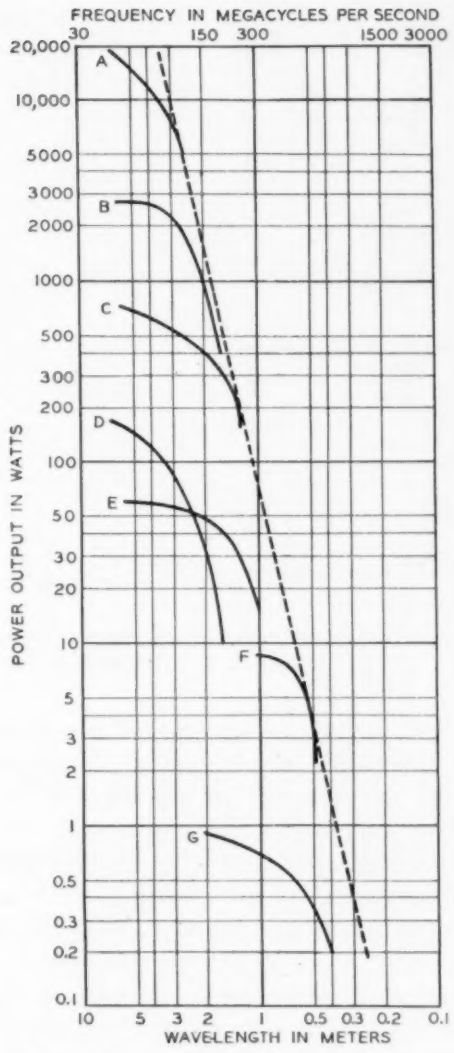


FIG. 1. Output frequency curves for some commercially available three element tubes operating as oscillators.

the metal and glass seals. Further ramifications of this effect will appear later.

Many of the factors which have been discussed may be compensated for in the design of a tube by a reduction in dimensions. In fact it can be shown that if all the dimensions of a vacuum tube are reduced in the same proportion, the transconductance, plate current, and amplification factor for fixed electrode potentials will remain unchanged, while the values of interelectrode capacitance, lead inductance, and electron transit time will be reduced in direct proportion to the reduction in size.[2] Unfortunately a reduction in dimensions without a corresponding reduction of all the operating potentials is

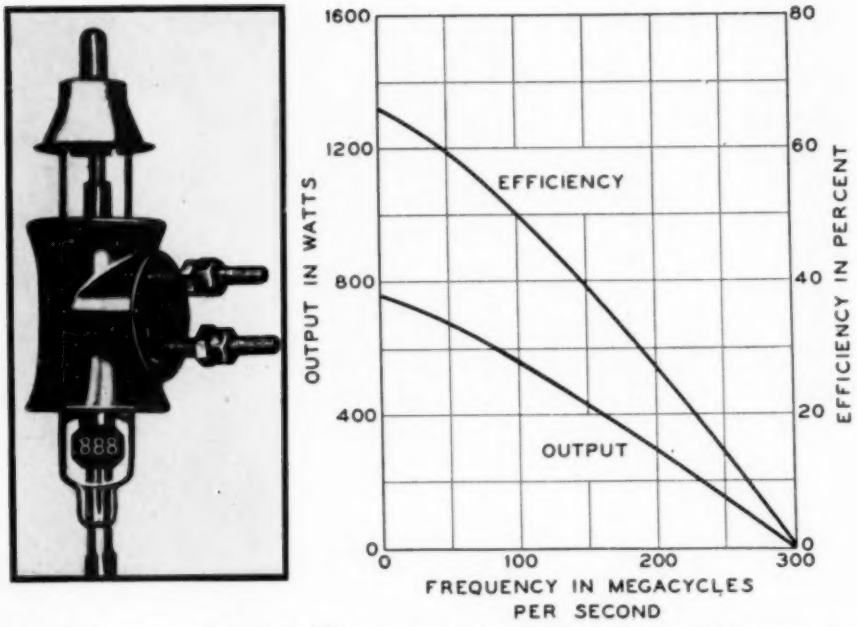


FIG. 2. A water-cooled tube which operates at frequencies as high as 300 megacycles per second.

possible only at the expense of an increased demand on the emission capability of the cathode. Of course an attempt to decrease the transit time by raising the electrode potentials without reducing dimensions leads to the same difficulty. The consequences of a 20 percent reduction in dimensions for three different electrical conditions are listed in Table I. Under the first assumption of constant potentials it will be observed that a 2500 percent increase is required in the cathode emission per square centimeter and in the anode dissipation per square centimeter as well. If, on the other hand, the emission demands placed upon the cathode are maintained constant, the usefulness of the tube is definitely impaired as evidenced by the reduction to 34 percent of the former value of transconductance and of the input impedance. The consequences of a compromise set of conditions are shown in the last column. Here the anode dissipation per unit area has been held constant. Under this assumption the output power will fall off as the square of the operating wave-length.

The limitation imposed by the available emission per unit of the cathode surface is fundamental. It restricts the frequency range for which thermionic tubes may be made to operate and it limits their ultimate performance at any frequency. This is the fundamental problem and one which should engage the attention of the physicist. The limitation imposed by the heat dissipating ability of the anode while serious, can be removed by suitable attention to details.

A third limitation is imposed by the high grid temperatures which result from a reduction in dimensions. This leads to the necessity of making provision for cooling the grids.[3] A more fundamental method of solving the problem which I also recommend for your consideration is to develop a material with extremely small electron

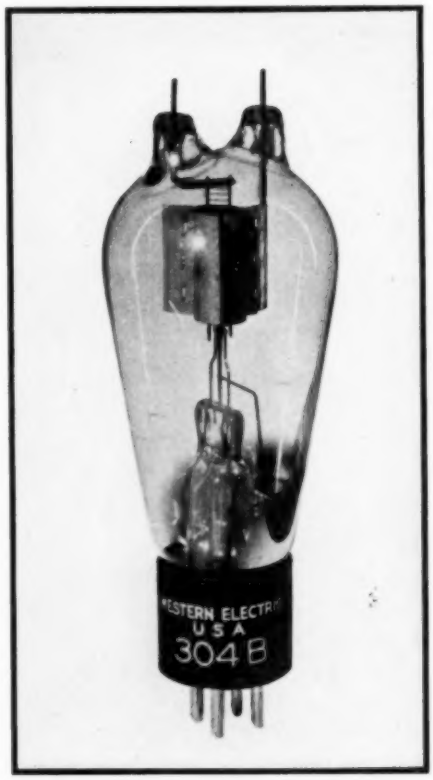


FIG. 3. A radiation-cooled tube for use at frequencies up to 350 megacycles per second.

emissivity even at elevated temperatures, and one which will not collect active coatings when in close proximity to an emitting cathode.

The severe mechanical problems encountered in attempts to reduce dimensions will be evident from a consideration of some specific tube structures.

The apparently inevitable reduction in output which occurs with increasing frequency is demonstrated by the data shown in Fig. 1.[4] On it will be seen a compilation of output *vs.* frequency curves for a number of different three element tubes. Two facts are significant. The first that all of the currents are the same general shape showing that the same factors are operating to limit the output, and second, that all of the curves approach a limiting curve. In accordance with the limits imposed by the scope of this symposium, only those tubes operating at frequencies higher than 300 megacycles will be considered.

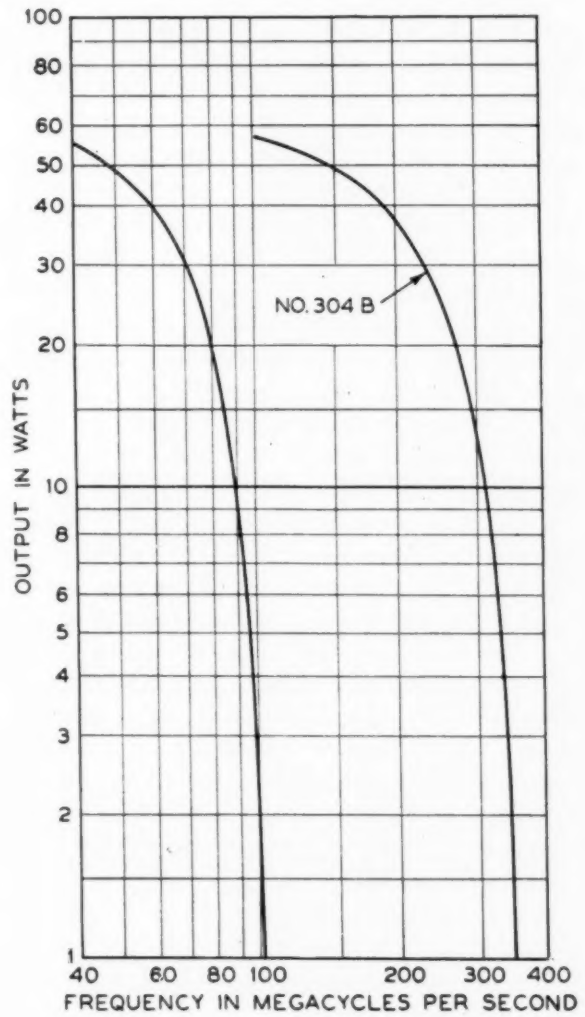


FIG. 3a. Output curve for table shown in Fig 3.

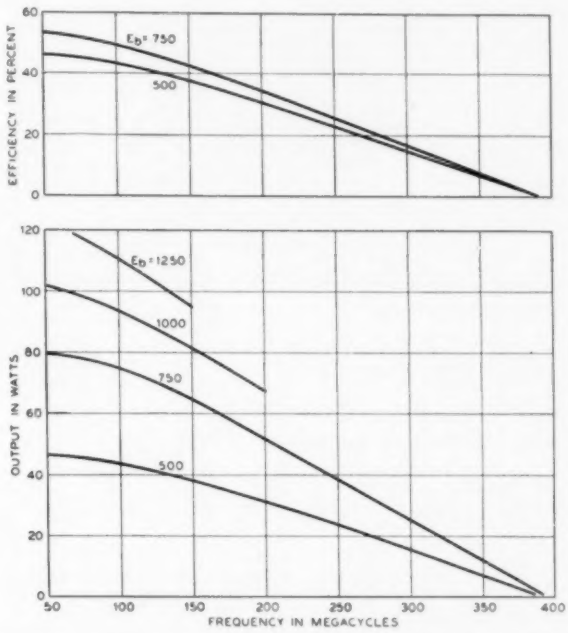
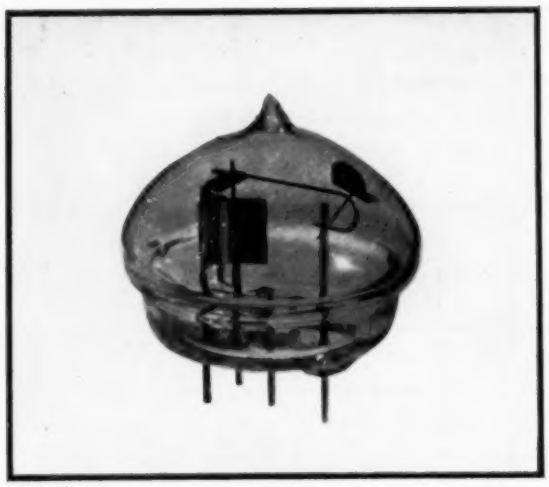


FIG. 4. Output and efficiency curves for two tubes of the type shown in Fig. 3.

The tube shown in Fig. 2 does not come in this category but is included because of its timeliness and because it represents the best that has so far been reported for water-cooled tubes.[4] This tube, the RCA 888, employs the conventional Housekeeper type of copper-to-glass seal and may be considered to be a to-scale model of the conventional water-cooled power tube with suitable modifications in the mechanics of construction consistent with the reduction in size. The output and efficiency curves for the tube as an oscillator are shown on the right. The decrease in output and efficiency with increasing frequency is typical, resulting from a combination of the factors we have just considered.

Figure 3 shows the Western Electric 304B, a radiation-cooled tube for use at frequencies as high as 350 megacycles.[3] The important features to be noted are the short lead length to the plate and grid, the absence of auxiliary supporting members, and the relative small size of the elements, all in accordance with the principles



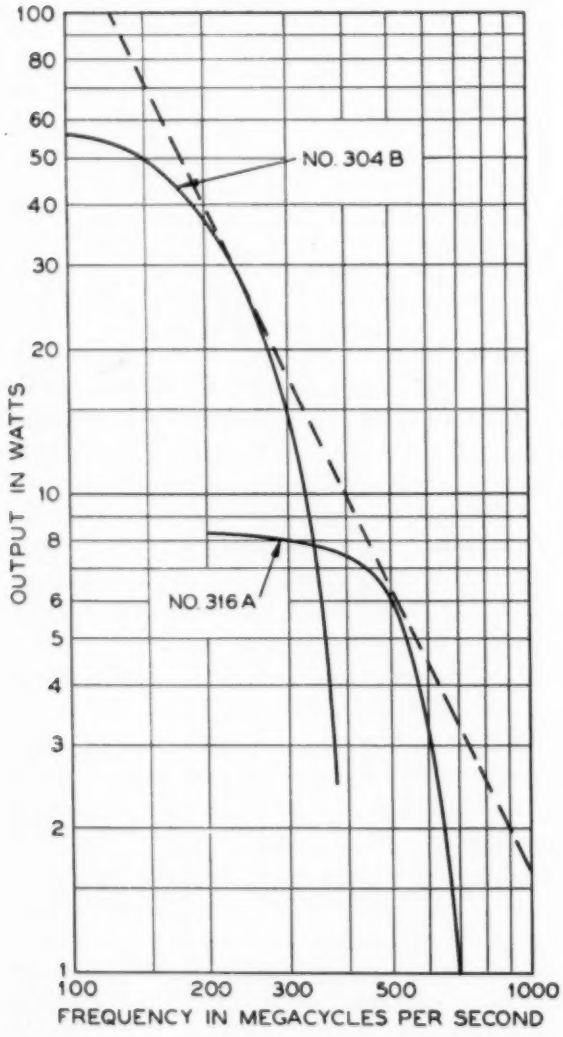


FIG. 5. A tube for use at frequencies as high as 700 megacycles per second.

just discussed. On the right of the figure is a plot of the output frequency curve for this tube compared to a curve for a tube of similar rating which is useful at lower frequencies. More detailed information is given in Fig. 4 which shows the output for two tubes in a push-pull circuit. The high efficiencies obtainable at low frequencies indicate that the electrical characteristics which are important for efficient operation in this frequency range have not been sacrificed in meeting the requirement of 300 megacycle operation. The fact that the upper frequency limit of operation is relatively independent of the operating plate potential indicates that circuit limitations rather than the electron transit time limitation are primarily responsible for the decrease in efficiency.

The tube shown in Fig. 5 (The Western Electric 316A) represents a still further departure from conventional structure with a corresponding increase in the frequency limit.[3] Unusual features of the design are the complete elimination of the usual press, the close spacing of the leads, and the special construction of the tube elements, particularly the grid made necessary by their small size. The grid is in the form of a number of straight wires parallel and equidistant from the axial filament and supported by cooling collars at each end. The comparison plot below indicates the improvement in performance made possible by this construction. From the data shown in Fig. 6 it will be observed that the limiting frequency for this tube varies with the applied anode potential indicating that the transit time effect is now largely responsible for the decreased efficiency. The relatively low efficiency for the lower frequency range results from a lack of sufficient filament emission. In a tube of this small size an increase in the filament emission to the value required by the high frequency considerations previously discussed is possible only by an impractical and unwarranted increase in the filament heating current. A photograph of one of these tubes in a circuit is shown in Fig. 7.

A review such as this would be incomplete without some mention of the tubes shown in Fig. 8. While the outputs obtainable are not large, the availability of tubes of this type for receiver uses has proven of great value to all

workers at these frequencies. Both triode and pentode types are available.[2] The triode can be made to oscillate at frequencies as high at 1000 megacycles while the pentode may be used as an amplifier as frequencies as high as 400 megacycles. The remarkable features of these tubes are their small dimensions and the unusual lead arrangements. A typical oscillator circuit employing an early form of this tube is shown in Fig. 9.

Turning now to a consideration of vacuum tubes that are still in the highly experimental stage, the tubes shown on the front cover represent a recent attempt to extend the frequency range.[5] They differ from the tubes previously described primarily in the lead arrangement. From the sketch of one of these tubes shown in the Fig. 10 it will be observed that the grid and plate elements are supported by wires which in effect go straight through the tube envelope, providing

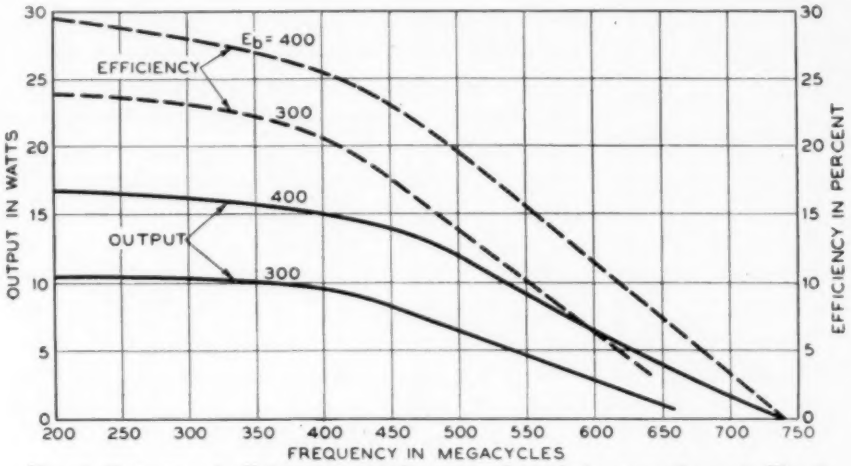


FIG. 6. Output and efficiency curves for two tubes of the type shown in Fig. 5.

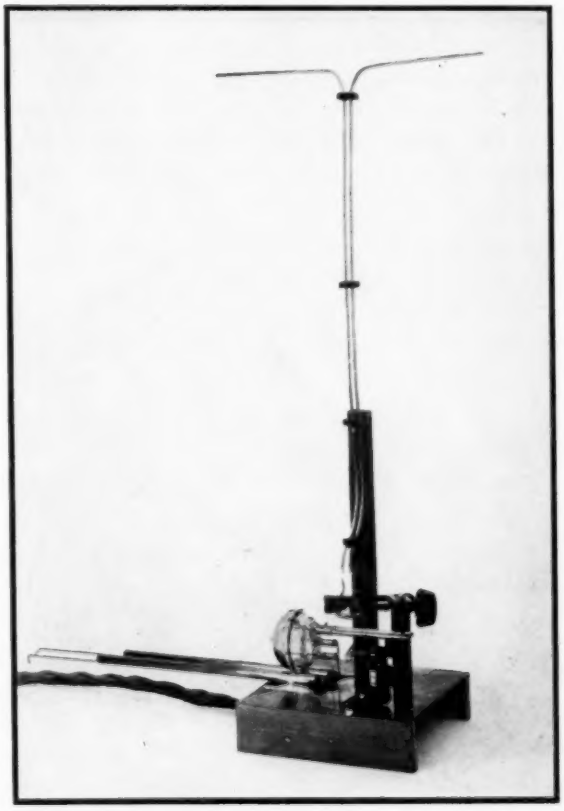


FIG. 7. A simple oscillator circuit for use at a frequency of 500 megacycles per second.

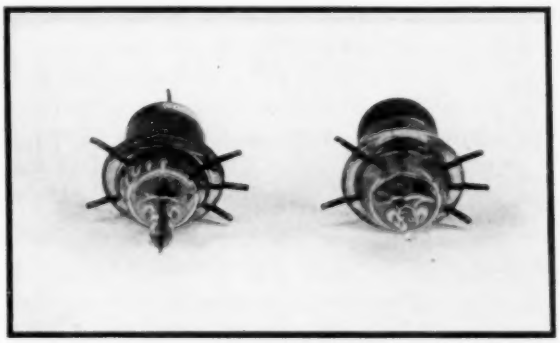


FIG. 8. Receiving type tubes for use at ultra-high frequencies.

two independent leads to each of these elements. Filament leads are at one end only and one of these leads is extremely short. Although a similar arrangement has been used in Barkhausen tubes to reduce circuit losses, as used here it possesses a number of unique advantages. The construction of the grid and plate elements is worthy of note. The grid consists of a series of tungsten loops supported by a cooling fin and projects into a slot in the block of graphite which acts as the plate element. One of these grids is shown in Fig. 11.

The double lead arrangement is responsible

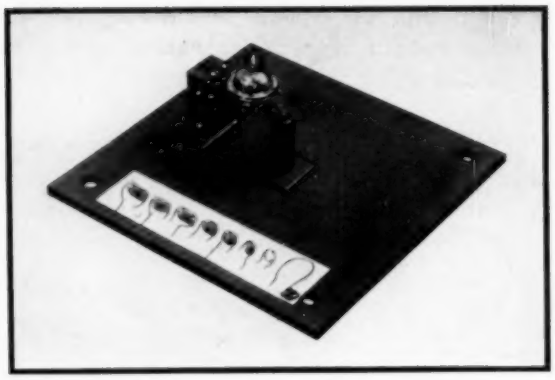


FIG. 9. A typical oscillator circuit using the acorn type tube.

for an increase in the upper frequency limit of the tube by a factor of from 1.2 to approximately 1.4. A typical oscillator circuit is shown in Fig. 12. Here the tube is mounted at the center of an equivalent half-wave Lecher system. It may be shown by a simple calculation that the natural frequency of such a system is greater than the frequency of the equivalent quarter-wave system formed by removing one set of leads. Since only half of the total charging current to the inter-electrode capacitances flows through each set of leads, the losses due to lead resistances are reduced. The balanced arrangement also results in a decrease in radiation losses. In the tubes under discussion the electron transit time limitation has been met by the use of extremely small interelectrode spaces, made possible by the unusual construction so that full advantage may be taken of the increased frequency range.

For the purpose of confirming the above conclusion output and efficiency curves have been obtained on the tubes when operating both single and double ended and on tubes identical in every respect except for omission of the extra set of leads. Typical results are shown in Fig. 13. It will be observed that the efficiencies for double ended operation are always higher than for the single ended case over the range covered by the experimental data. In fact usable outputs are obtained at frequencies well beyond the point where the single ended tube fails to operate. The ratio of the cut-off frequencies for the two modes of operation happens to be 1.2 for the particular conditions under which these data were obtained.

The outputs obtainable from these tubes are shown in Fig. 14 compared with those obtained from two of the tubes previously discussed. The two sloping lines are for a fixed value of the ratio of output to the square of the wave-length, one line being for a ratio of four times that represented by the other line. The improvement in output by approximately this factor of four made possible by the present departure in design is at once evident. Special attention is called to the output and upper frequency limit of the small tube. Typical values are 3 watts at 1200 megacycles, 2 watts at 1500 megacycles and 1 watt at 1700 megacycles with a limiting frequency of 1870 megacycles corresponding to a wave-length of 16 centimeters. So far as the writer is aware this represents the highest fundamental frequency which has so far been produced by tubes of the negative grid type.

So much for the use of vacuum tubes as oscillators. The use of the conventional type of vacuum tube as an amplifier greatly exceeds its use as an oscillation generator, at least in communication applications. In fact its ability to amplify has contributed much more to the development of our present day long distance communication, whether by wire or by radio, than has its ability to oscillate. Fortunately, vacuum tubes developed for use primarily as oscillators at ultra-high frequencies are also

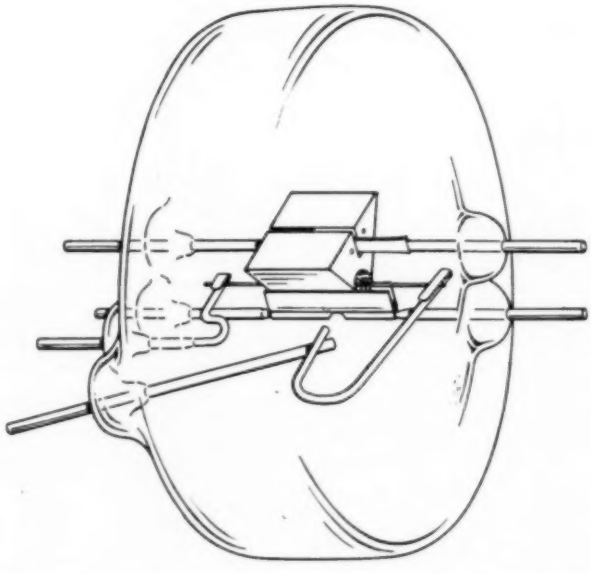


FIG. 10. Section view of a double lead tube showing lead arrangement.

useful as amplifiers. To understand how this comes about it will be necessary to consider briefly the causes for instability as an amplifier.

The primary cause for instability of the triode is the interaction between the input and output circuits which results from coupling between these circuits provided by the grid-plate capacitance. A second source of coupling is any common impedance in the two circuits in the nature of self or mutual inductance of the tube leads. This second form coupling is referred to as impedance coupling as contrasted with admittance coupling caused by the interelectrode capacitances. At moderately high frequencies this impedance coupling is usually of negligible importance.

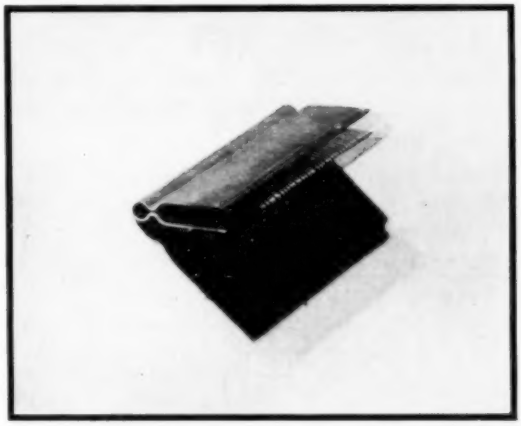


FIG. 11. Grid structure used in one of the double lead tubes.

Stable operation is thus possible when suitable means are provided to compensate or neutralize the admittance coupling. An ultra-high frequencies impedance coupling can no longer be neglected. It may, of course, be minimized by the use of short leads. Consequently the triodes which have been described for use as oscillators are also good amplifiers at ultra-high frequencies.

The ultimate solution to the problem is to provide independent leads to the input, output, and admittance neutralizing circuits so that impedance coupling because of common leads is definitely eliminated. The double lead tubes just described will be seen to partially fulfill these conditions. It will be observed that the only common impedance remaining is that caused by one filament lead, and that this lead is extremely short.

An additional circuit refinement is found advantageous with these tubes. In general two methods of neutralizing admittance couplings are possible. One is to compensate for the potential which the disturbing admittance would introduce in the input circuit by means of a circuit which by itself would introduce another potential of opposite polarity. All of the more common capacitance neutralization schemes fall in this category. A second method is to resonate the offending admittance at the operating frequency so that the resulting parallel admittance is reduced to a very low value. In the triode circuit this takes the form of an industance connected between the grid and plate of the tube and adjusted to resonate with the grid-plate capacitance. When applied to the double lead tubes the neutralizing circuit can be connected to one set of the grid and plate terminals, and the input and output circuits to the remaining terminals, thus minimizing the otherwise unavoidable impedance coupling, which would result from the inductance of grid and plate leads. The usefulness of this scheme has been demonstrated by the construction of an amplifier using the larger size double lead tube. An output of 60 watts at 144 megacycles with an efficiency of 30 percent for class *B* operation was reported with this amplifier. The stability, band width and distortion were comparable with results obtained on pentodes of similar rating at lower frequencies.

In view of the many advantages of multi-element tubes at lower frequencies, it is reasonable to assume that multi-element tubes for use at ultra-high frequencies will some day become available and will find wide application. A start in this direction has been made with the development of the experimental push-pull pentode[6] tube shown in Fig. 15. It consists of two sets of elements mounted on the opposite sides of a relatively large cylindrical shield. This shield is formed by two coaxial cylinders which act as supports for the screen and suppressor grids, as low impedance connector between opposite sets of elements, and as a radiofrequency by-pass condenser between the suppressor and screen elements. The control grids are of the fin type

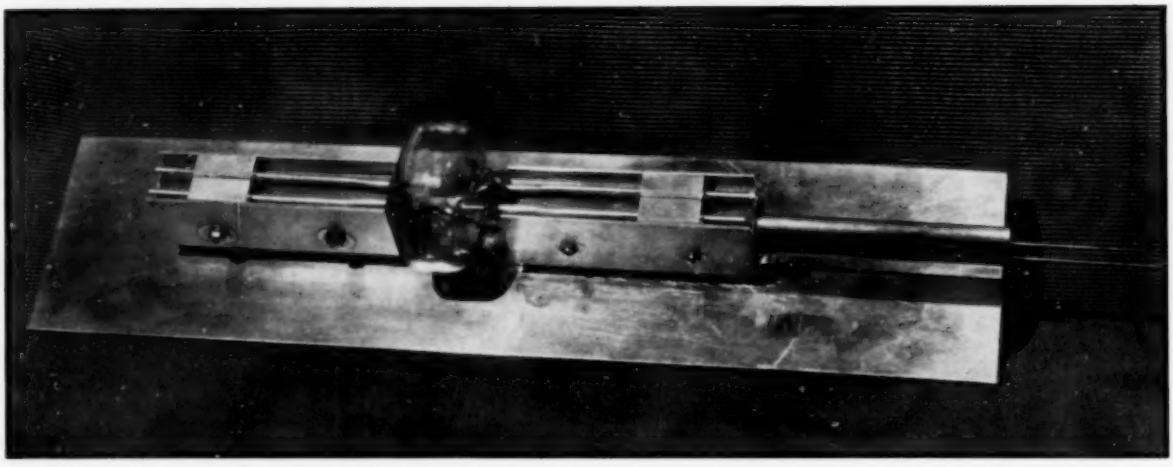


FIG. 12. A typical oscillator circuit using one of the tubes shown on the front cover.

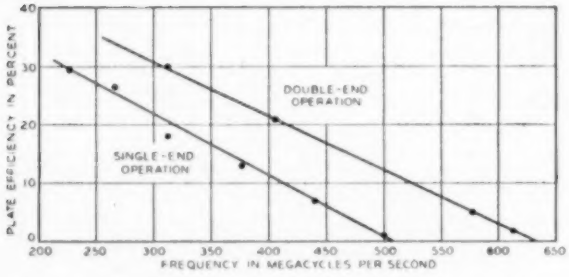


FIG. 13. Comparison plot showing the effect of double-end operation.

previously described in connection with triode tubes. Still further details are evident from the section view shown in Fig. 16. Other interesting features of the design are the complete shielding provided between input and output circuits by these supporting cylinders and the absence of any leads common to both input and output circuits. Adequate cooling of all grids is provided by their method of support.

This tube differs in its electrical characteristic from the conventional pentode in two important respects. The first is the great reduction in inductance of the leads which, coupled with a moderate reduction in the interelectrode capacitances, overcomes the high frequency circuit limitation discussed in connection with oscillators. The second is the relatively high value of input impedance which comes about because of the very small interelectrode spacings. Measured values of the input resistance as a function of frequency are shown in Fig. 17 compared with the value for a typical conventional type tube and the values for the acorn type receiving tubes. The value of 30,000 ohms at 150 megacycles is to be compared with 2000 ohms, a typical value for two conventional tubes in push-pull. At 300 megacycles the input resistance is still above

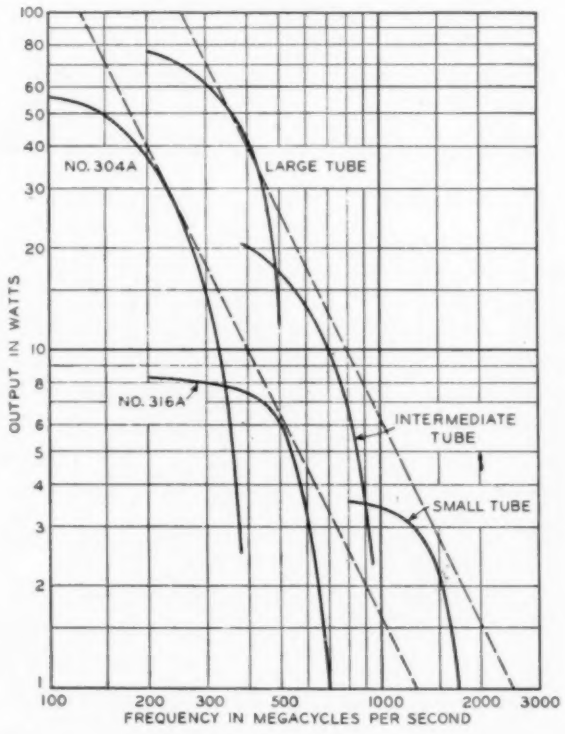


FIG. 14. The output of the double-lead tubes compared with outputs obtainable from the tube shown in Figs. 3 and 5.

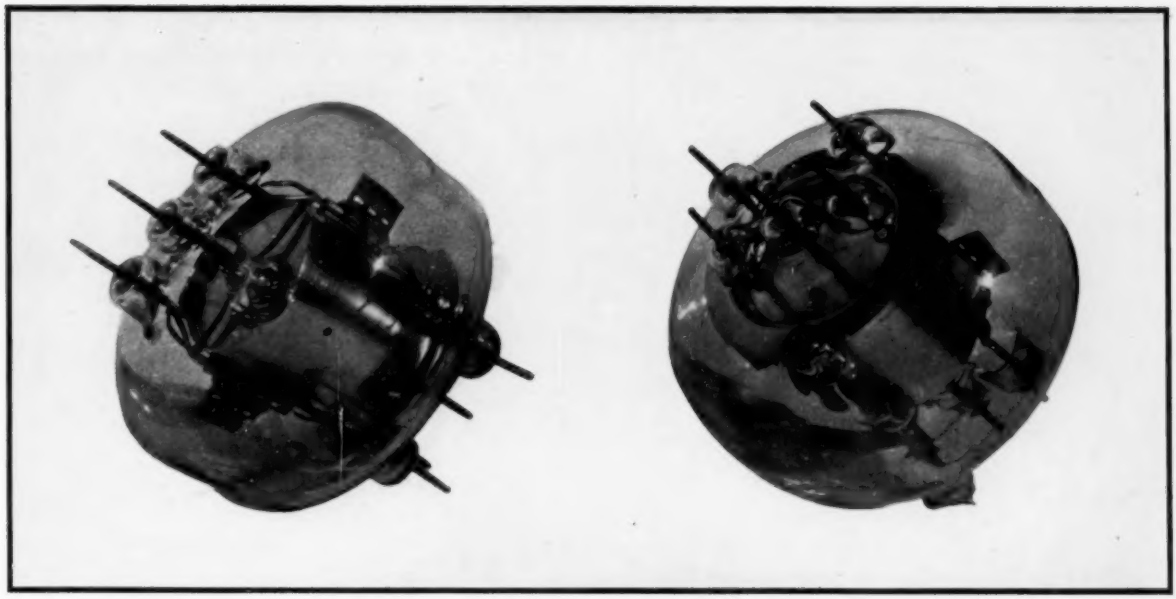


FIG. 15. An ultra-high frequency double pentode vacuum tube.

5000 ohms while for conventional tubes it is so low as to make them completely inoperative.

The push-pull pentode has been found useful as a high quality class *A* amplifier, a class *B* amplifier, a frequency multipler and as a modulator at frequencies in the vicinity of 300 megacycles per second. Its performance in these various modes of operation is quite comparable to the performance of conventional pentodes of similar ratings at much lower frequencies. Stable operation with some gain has been obtained at frequencies as high as 500 megacycles. When operating as a class *A* amplifier at 150 megacycles an output of 1 watt is obtained with the distortion 40 db below the fundamental. Under these conditions the stage gain is 20 db. Outputs of 10 watts with a plate efficiency of 60 to 70 percent and a gain of 10 db are obtained with class *B* operations.

It is customary to conclude a review such as this with a few words of prophecy as to what the future may bring. Baring revolutionary discoveries future progress in extending the frequency range of the negative grid tube seems to be dependent upon improved construction techniques which will permit the use of smaller dimensions, and strangely enough upon the development of both better and poorer electron

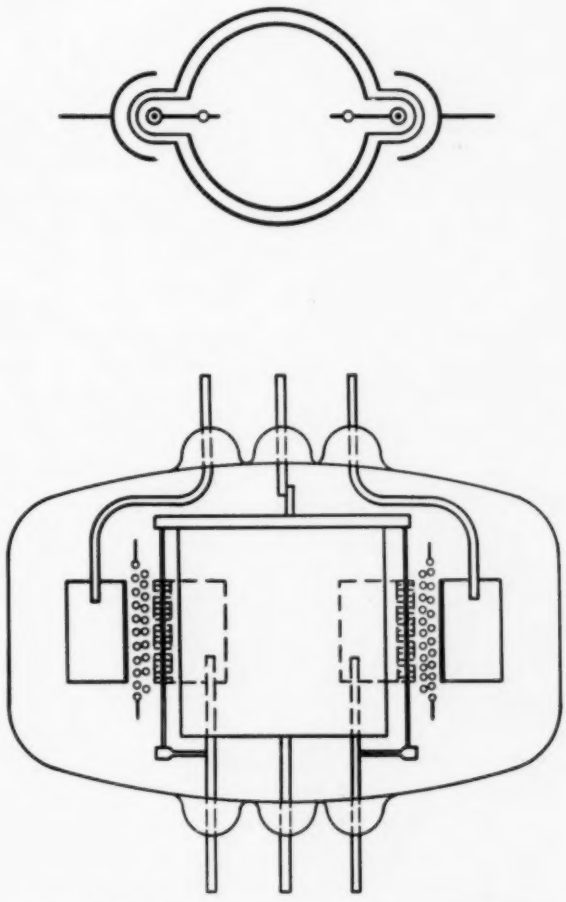


FIG. 16. Section view of the tube shown in Fig. 15.

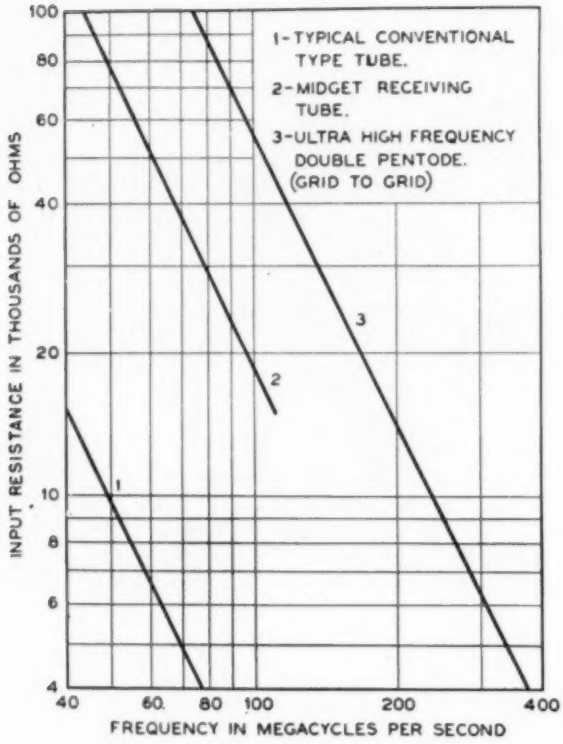


FIG. 17. The input resistance as a function of frequency for the push-pull pentode.

emitters. It also seems reasonable to assume that the full capabilities of the existing tube structures have not been utilized. The use of harmonic components of oscillators and improved circuit technique in the use of frequency multipliers offer interesting possibilities. Enough has been said I think to indicate that the negative grid tube will be able to meet the demands of the circuit designer at least for some time to come.

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5. A. L. Samuel, "A Negative-Grid Triode Oscillator and Amplifier for Ultra-High Frequencies," Proc. I. R. E. **25**, 1243 (1937).
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The pure scientist concerns himself with the study of the materials, forces and phenomena of nature. The applied scientist bridges the gap between science and its use, and his function is to interpret and extend in order that utility may ensue. The engineer bridges the gap between science and the public, and his function is to develop the applications of science in such a manner that they may fit beneficially into the existing organization of civilization.—KARL T. COMPTON

Here and There

New Appointments

Dr. Clarence Zener has accepted a position with the College of the City of New York. Formerly, Dr. Zener was at Washington University, St. Louis, Mo.

Dr. Edward Jay Schremp, who received his Ph.D. from the Massachusetts Institute of Technology in theoretical physics in June, 1937, has been appointed to the Instructorship at Washington University, St. Louis, Mo., vacated by Dr. Clarence Zener.

★

Dr. Victor Weisskopf of Copenhagen arrived in this country September 28 to take up his new duties as instructor in physics at the University of Rochester. For the past several years Dr. Weisskopf has been engaged in theoretical research in the field of nuclear phenomena in collaboration with Professors Niels Bohr, W. Pauli, W. Heisenberg and other European leaders in this field. He will bring to this country the first reports of the recent Copenhagen Conference on theoretical physics.

★

Mr. Robert E. Stephens of the University of Pittsburgh has recently accepted a position as physicist with the Mead Paper Corporation, at Chillicothe, Ohio.

★

Mr. Robert H. Osborn of the University of Pittsburgh has accepted a position with the Hercules Experiment Station, Wilmington, Delaware. He was formerly a graduate assistant at the University of Pittsburgh.

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Dr. T. Smith Taylor, professor of physics at Washington and Jefferson College, Washington, Pa., has been appointed manager of the engineering laboratory and experimental department of the Diehl Manufacturing Company, the electrical division of the Singer Manufacturing Company, Elizabethport, New Jersey.

★

Dr. Robley D. Evans, assistant professor of physics at the Massachusetts Institute of Technology, recently received the first Theobald Smith award in medical science, consisting of a bronze medal and one thousand dollars, for his researches, which have led to a method of detecting radium poisoning before its fatal stage and a treatment for extracting radium from bones.

Nature, September 11, 1937

Physical Basis of Metallic Properties

A Round Table discussion on the Physical Basis of Metallic Properties will be held at Atlantic City on the evening of October 18 in connection with National Metals Congress sponsored by the American Society for Metals. The general subject for discussion will be Elasticity both from the point of view of the physicist and from that of the engineer. The following program is planned:

Subject: **Elasticity.** L. W. McKeehan, Chairman.

1. **True Stress-Strain Curves**
   (a) **for single crystals:** Discussion leader—S. L. Hoyt
   (b) **for polycrystalline materials:** Discussion leader—R. K. Haskell
2. **Internal Dissipation of Energy in Metals for Small Cyclic Strains** Discussion leader—R. L. Wegel.

Anyone who is interested in this field is invited to be present and to take part in the discussions.

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Journal of Applied Physics

For November

Fundamental Mechanisms in the Ionosphere, *by* **N. E. Bradbury**

Terrestrial Magnetic Variations and the Ionosphere, *by* **A. G. McNish**

Sudden Disturbances of the Ionosphere, *by* **J. H. Dellinger**

The Nature of Bright Chromospheric Eruptions, *by* **R. S. Richardson**

Contributed Research Papers on Radiographic Properties of Intensifying Screens, A Characteristic of the Copper Arc During Formation Period, Electrical and Luminescent Properties of Willemite Under Electron Bombardment and the Cathode Region in the Glow Discharge.

★

Harvard School of Engineering

Harald M. Westergaard, who was named Gordon McKay Professor of Engineering at Harvard last fall, following twenty years on the engineering faculty of the University of Illinois, has been appointed Dean of the Harvard Graduate School of Engineering. In this new post he succeeds Dean Harry E. Clifford, who became emeritus this year.

At the University of Illinois, he was Instructor in Theoretical and Applied Mechanics, 1916–19; Associate, 1919–21; Assistant Professor, 1921–24; Associate Professor 1924–27; and Professor, 1927–36. He is a member of the American Society of Civil Engineers, the Danish Institu-

tion of Engineers, the Dansk Selskab for Bygningsstatik, the Gesellschaft für angewandte Mathematik und Mechanik, the Society for the Advancement of Scandinavian Studies, Phi Beta Kappa, Tau Beta Pi, and Sigma Xi.

★

Committee on Electrical Insulation

The Tenth Annual Meeting of the Committee on Electrical Insulation, Division of Engineering and Industrial Research, National Research Council, will be held in New York City on November 4th and 5th. For this meeting the Committee will be the guests of the Consolidated Edison Company of New York. There will be two technical sessions on Thursday, the 4th, and one on Friday, the 5th. The speaker at the annual dinner will be Dr. A. von Hippel of the Massachusetts Institute of Technology. The afternoon of Friday, the 5th, will be devoted to committee conferences and to visits of inspection. Dr. John B. Whitehead, Johns Hopkins University, is chairman of the Committee.

★

Meeting of Physicists of Upper New York State

For some time there has been a growing sentiment toward the formation of a section of the American Physical Society for upper New York state. After due canvassing of the members of the Physical Society of that territory, plans have been formulated for a meeting to be held at Cornell University under the auspices of the American Physical Society on Saturday, November 6th.

At that meeting final action will be taken on the question as to whether a section of the American Physical Society shall be formed. In the event of such formation it is contemplated that membership shall be available to teachers of physics in colleges and in high schools, to physicists in the industries and to other physicists without regard to membership in the American Physical Society.

A program, to which all interested physicists are invited, has been prepared, starting at 10 A.M. and comprising the following:

Address of Welcome, *Edmund E. Day, President of Cornell University*
A Quarter Century of Progress in Physics, *L. A. DuBridge, University of Rochester*
Physical Problems of Industrial Radiography, *Herman E. Seemann, Eastman Kodak Company*
Cooling an Automobile Engine, *L. P. Saunders, Harrison Radiator Division, General Motors Company*
The Theory of Electrical Measuring Instruments, *F. C. Bobier, General Electric Company*
Abrasives and Their Uses, *E. T. Hager, Carborundum Company, Niagara Falls, New York*
Physics in the Small College, *Paul F. Gaehr, Wells College*

Committee

G. H. CAMERON, *Hamilton College*
R. C. GIBBS, *Cornell University*
H. P. GAGE, *Corning Glass Company*
L. G. HECTOR, *University of Buffalo*
P. I. WOLD, *Chairman, Union College*

★

Scientific Aids to Learning

A comprehensive survey of how radio, sound recording and reproduction, motion pictures, photography and other scientific achievements may be applied to promotion of learning is to be conducted by a special committee of the National Research Council.

Dr. Irvin Stewart, now vice chairman of the Federal Communications Commission, will head the active investigations as director upon the expiration of his term on the FCC June 30. President James B. Conant of Harvard is chairman of the committee consisting of Dean Vannevar Bush of Massachusetts Institute of Technology; President L. D. Coffman of the University of Minnesota; Dr. Frank B. Jewett, president of Bell Telephone Laboratories; Professor Ben D. Wood of Columbia University; Bethuel M. Webster, New York attorney and Dr. Ludvig Hektoen, chairman of the National Research Council.

The new committee on "scientific aids to learning" will establish offices in New York and appoint experts and consultants to aid in its inquiries. The first activity will be in the field of educational broadcasting and will consist of a survey of the work and experience of the National Advisory Council on Radio in Education. Funds from the Carnegie Corporation will support the committee's activities.

★

Sine Curve Plotter

The A. Lietz Company, of 913 S. Grand Ave., Los Angeles, California, announce the manufacture of a new instrument, the Sine Curve Plotter. The Plotter is simply a chart engraved on a 10"–45° drafting triangle. A sine or cosine curve of any percentage amplitude is plotted by merely moving the triangle to successive points on the curve axis and placing dots at the appropriate edge-graduations. All time-consuming construction lines associated with the conventional graphical methods are eliminated. Inasmuch as the Plotter chart is incorporated in a high quality triangle an instrument of double utility results.

★

NBC Starts New Television Tests

¶ Field tests of RCA experimental television with the new 441-line definition have been resumed by the National Broadcasting Company on the largest scale ever undertaken in the United States. The tests will continue throughout the spring and summer months.

Test programs will be televised daily from the NBC transmitter in the Empire State Tower. NBC has been on the air with television since 1931, and has had the only television station in operation in New York City for the last four years. Quality of reception will be checked by NBC engineers on more than 75 receivers placed at selected points throughout the metropolitan area.

O. B. Hanson, NBC chief engineer, said the object of the new tests, which represent the latest development in seven years of television experiment by NBC, is to determine the home program potentialities of high definition television. RCA television of 441-line definition has been in operation in the laboratory since last December, but this will be the first test under practical field conditions.

In similar field tests of 343-line pictures held as early as last summer, NBC engineers received satisfactory pictures as far distant as 45 miles from the Empire State trans-

mitter. Last December tests on this basis were discontinued to allow for necessary alterations to change the equipment over to the finer definition 441-line system.

While testing the quality of 441-line transmission, NBC also will conduct extensive experiments into television programming and production. Elisabeth Rethberg, of the Metropolitan Opera Company, Mario Chamlee, Walter Damrosch, Helen Hayes and Lanny Ross, are among the numerous radio, stage and screen artists who will appear before the iconoscope, in order that the engineers and production men may study the technique of television performance and production.

Veterans of nearly a decade of television development, the NBC engineers state that there are still many major problems to be solved in the televising of different colors, scenes and types of performance. A tentative schedule is under consideration which would provide for four evenings a week on alternate weeks. A complete technical staff will be on duty in the television studio to assist the program and production men. Leaders in stage design, textiles, decoration and fashion will be invited to cooperate with NBC in solving the many problems of television staging.

★

Opportunities for Physicists in Geology

¶ In a recent address, Dr. William Otis Hotchkiss, president, Rensselaer Polytechnic Institute, and vice president of the Geological Society of America, discussed the opportunities for collaboration of physicists and engineers in the field of geology. Quoting Dr. Hotckhiss "Samples taken with a core drill in solid rock return good samples of the solid material, but when a weak layer such as a clay seam or a disintegrated part of the rock is penetrated by the core drill, the sample is not at all representative of the material. One is forced to inquire of himself how useful are tests that can reflect the probable behaviors of only the strongest part of the total aggregate about which information is needed. Furthermore the tests must be carried on under conditions that necessarily cannot equal conditions under which the material occurs in place. The material as it is to be used will be subjected to three dimensional stresses from its natural surrounding as well as the stresses from the new load that is to be superimposed. We have no perfectly satisfactory method of duplicating these conditions during the test because we do not know them.

"If there is difficulty with the relatively easy sampling method of core drilling in solid rock, what can we expect from the samples taken under the much more difficult methods of sampling the unconsolidated materials? Much effort has been devoted to finding ways of securing undisturbed samples of these softer materials. The result has as yet failed to give the desired satisfaction. The disturbance caused by the tool used to secure the sample always to some degree alters the sample before it is removed from its setting. If this setting is below the water level the sample of unconsolidated material is an aggregate of certain sizes and shapes and kinds of mineral particles with a certain percentage of voids filled with a water solution under the pressure there existing. The water may have in solution either air or gases or both in amounts determined by the prevailing equilibrium of pressure and temperature. When the sample is removed to the surface both temperature and pressure are changed, and the liberation of gas, or the increase in internal pressure if none is liberated, will produce a change in the sample which makes it impossible to determine by any form of test the exact way in which that material will behave in place. The best tests will give us only an approximation which at present can only be interpreted with the judgment acquired by observation and experience acquired under similar situation.

"Do not interpret me as believing such sampling methods and tests as we now have are useless. They are very useful. They have shown many results that have been satisfactorily checked by later experience. My criticism is pointed at their lack of perfection with the purpose of emphasizing the fact that we need to know more than these tests now tell us. The field for the development of new tests is wide open. We have confined most of our efforts to the present time to samples we can remove from their place and take to a laboratory. I would suggest that it might be very profitable to devote the thoughts of some of the men carrying on this research to the consideration of tests that might be applied without removing a test sample. I shall not suggest any details of method but only refer to the whole gamut of the methods of physics as worthy of investigation. It is from the united efforts of physicists and engineers that greatest advance in method is to be expected. Perhaps I should add that the geologist might occupy a modest place in the background as an advisor. The physicists need to have their interest in the problem aroused. Few of them are interested at present in problems of this nature. Perhaps the first interest might be developed through the geophysicists. They have already done much in the beginning of the study of surface applied physical methods of economically valuable deposits of minerals. They have already done some work in relation to foundation materials. If the attention of geophysical researchers was directed to these important problems that confront the engineer there is no doubt that much of interest and value would result."

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New Booklets Received

The General Radio Experimenter, Vol. 12, Nos. 3 and 4, August–September, 1937. This issue contains a description of a new instrument and a new circuit for coil or condenser checking and notes on the standardizing of the Standard Signal Generator and the Standard Frequencies for the Musician.

Du Mont Oscillographer, Vol. 1, Nos. 6–7, August–September, 1937. This issue contains articles on "Europe turns that television corner," and "an oscillograph amplifier design."

The Educational Focus, September 1937; 32 pages. This issue contains articles on domestic optical glass, chromosome demonstration material, projecting biological specimens, Willebrord Snell, experiments with yeast, and an article on micro films.

Some of the New Books

Principles of Quantum Mechanics. ALFRED LANDÉ, Pp. 117+xii. The Macmillan Company, New York, 1937. Price $2.25.

In this book Professor Landé has given us what is perhaps the best treatment of the origin and fundamentals of quantum mechanics yet to be published. The style of writing is concise but always clear and readable. One cannot help being impressed by the elegance of the exposition and by the fact that this quality arises from its directness and simplicity.

The aim of the author is to show that the mathematical structure of quantum mechanics is designed to bridge the gap between wave and corpuscular modes of description of physical phenomena. The hypothesis of perfect complementarity of these two ways of speaking is taken as the essential guide in constructing the theory. In the case of simple phenomena the bridge is easy to construct and leads to the most fundamental laws of the quantum theory. These fundaments are then logically generalized to cover the description of more complicated problems and the validity of the generalizations established. We finally see the completed theory and understand it because we have examined each step in the building process.

The book, in addition to an important preface and introduction, is divided into five parts. The first shows how the principle of complementarity may be applied in simple examples to derive the best known and most general of the laws of quantum mechanics. The second part treats the uncertainty principle of Heisenberg and the third derives the quantum-mechanical theorems of superposition and interference. In part four, Landé gives a good treatment of the "correspondence" between classical and quantum mechanics and develops the essentials of transformation theory. The final section, in the form of a mathematical appendix, treats the invariance of quantum-mechanical laws to canonical and unitary transformations.

In his preface, the author acknowledges his indebtedness to Heisenberg's *The Physical Principles of the Quantum Theory* and the two works are indeed similar in many respects. However, Landé has gone further in clarifying inner relationships of the theory than Heisenberg, and has achieved marked success in eliminating nonrational and inconsistent statements from the language of quantum mechanics.

No serious student of modern physics should fail to read Landé's *Principles of Quantum Mechanics.*

L. A. YOUNG

Elektrische Messgeräte und Messeinrichtungen. A. PALM. Pp. 231+ix, Figs. 205. Verlag von Julius Springer, Berlin, 1937. Price, bound, RM 16.50.

This book is written in the form of a textbook. Pictures and diagrams of many different forms of meters are shown.

Electricity and Magnetism. A. W. HIRST. Pp. 388+xv, Figs. 205. Prentice-Hall, Inc., New York, 1937. Price $4.50.

Among our Contributors

Dr. C. S. Venkateswaran was born at Malabar, South India, May, 1905, and took his B.A. (Hons.) degree in physics, M.Sc. degree (research) in applied physics and D.Sc. degree in pure physics at the Madras University in 1928, 1932 and 1937. He was lecturer in physics at the Union Christian College, Alwaye, 1928–1930, and University Research Scholar in the Presidency College, Madras, 1930–1933, student and assistant in the physics department, Indian Institute of Science, 1933–1935, and from 1935 to date assistant superintendent, Central Workshops, Indian Institute of Science, Bangalore.

Dr. Cecil T. Lane received his training at McGill University, Montreal, and at the University of Munich, Germany. He has been at Yale University since 1932 as Sterling Research Fellow (1933–34) and Research Assistant in biophysics (1934–36). During the present session he is an instructor in physics at the above institution.

Professor William W. Hansen is also a contributor to this issue. A photograph and biography of Dr. Hansen appears on page 273 of the April issue of this Journal.

Contributed Original Research

Temperature Dependence of Diamagnetism in Gamma-Brasses

C. T. LANE
Sloane Physics Laboratory, Yale University
(Received July 26, 1937)

A series of measurements on the temperature dependence (20–700°C) of the diamagnetic susceptibility of several gamma-phase brasses are reported. At room temperature the susceptibility is a linear function of composition, in agreement with previously reported work. At higher temperatures, however, this linearity no longer holds, the departure being greater at the higher temperatures. At the copper-rich end of the phase the susceptibility increases with temperature, while at the zinc-rich end the reverse is true, and the susceptibility is sensibly constant near the theoretical composition Cu_5Zn_8. The bearing of these results on the Bloch theory of metals is discussed.

THE modern theory of the electronic properties of metals, initiated mainly by A. Sommerfeld and greatly extended by Bloch and others, has proved to be of great utility in understanding, qualitatively at least, a wide variety of metallic phenomena. The theory has met with particular success in clearing up some troublesome questions connected with the magnetic properties of metals and alloy systems. The older quantum-mechanical model of Pauli, which treated solely a degenerate electronic gas in a constant potential field, was successful in explaining why many metals (most, in fact) have a susceptibility nearly independent of temperature. However, a few metals (bismuth, antimony and graphite) showed not only a very high diamagnetic susceptibility, much higher than the Pauli model could account for, but also this susceptibility was markedly temperature dependent. These metals became known variously as "abnormal diamagnetics" or "crystal diamagnetics." A very large amount of experimental work has been done on them, especially on bismuth.

Prior to the advent of the Fermi statistics, a phenomenological theory had been proposed by Ehrenfest to account for these anomalies. He proposed that, for these metals, a certain number of electrons moved in large orbits, encircling several atoms. This accounted for the large diamagnetism; the disturbance of these orbits due to thermal vibrations of the lattice explained the temperature dependence of the susceptibility.

The interesting discovery of Goetz and Focke[1] that very dilute solid solutions of several metals in bismuth, when prepared as single crystals, showed radically different magnetic properties only to be explained by Ehrenfest's theory with the addition of some none too plausible hypotheses. Using the Bloch model, however, H. Jones[2] has been able to show that these experiments were in very satisfactory agreement with theory and further was able to calculate the susceptibility of pure monocrystalline bismuth, also in close agreement with the experimentally determined value.

It had long been known that alloys of copper and zinc over a certain narrow range of composition (the gamma-phase) possessed very large diamagnetic susceptibilities. Bernal[3] appears to have been the first to have pointed out that

[1] A. Goetz and A. B. Focke, Phys. Rev. **45**, 170 (1934).
[2] H. Jones, Proc. Roy. Soc. **147**, 396 (1934).
[3] J. D. Bernal, Trans. Faraday Soc. **25**, 367 (1929).

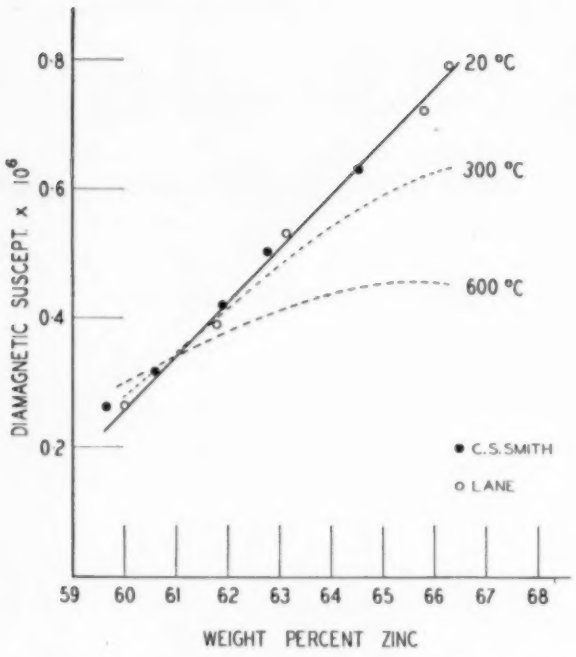

FIG. 1. Curves showing the relation between specific susceptibility and zinc content for a number of gamma-brasses.

alloys in the gamma-phase were strikingly similar in many of their properties to bismuth, and he suggested that the electronic behavior in the two cases was the same. The first reliable measurements on the susceptibility, at room temperature, of pure well-annealed gamma-phase alloys were recently reported by C. S. Smith.[4] He found that the diamagnetic susceptibility (at room temperature) increased linearly with zinc content over the gamma-region. Measurements were reported also for the gamma-phases in the systems Ag-Zn, Cu-Cd, and Ag-Cd. Making use of Bloch's theory, Jones[5] showed that, despite great differences in structure between bismuth and the gamma-alloys,[6] the latter should show magnetic properties very similar to those of Bi and Sb, and at the same time a rough calculation of the actual susceptibility for the alloy was in good agreement with Smith's measured value for γ(Cu-Zn).

Since, as was mentioned in the beginning, Bi and Sb show an abnormally large dependence of susceptibility on temperature it was thought worth while to make some observations on this point in the case of a gamma-phase alloy, since such measurements do not appear to have been previously reported. The alloy γ(Cu-Zn) was chosen since this exhibits the largest known diamagnetism for this class. Further, the gamma-phase in this alloy remains stable for all compositions at which it is possible up to a high temperature and no superstructure has been reported to occur in the low temperature range.

TECHNIQUE

The alloys were synthesized from the purest available materials. One set of castings was supplied by Dr. C. S. Smith using cathode copper and Bunker Hill zinc. A second set was made up using electrolytic copper (99.995 percent) with oxygen as the chief impurity and zinc of exceptional purity kindly supplied by the New Jersey Zinc Company. The total impurities (mainly Cd and Pb) in this latter material were present in amount less than 0.00025 percent.

In order to be readily measurable it was necessary to have the alloy in the form of cylindrical rods about 3 mm in diameter. Since gamma-phase alloys are exceptionally brittle and hence cannot be worked, these rods were produced as follows. The castings were first reduced to powder in a mortar and this powder was packed into a pure graphite crucible. The crucible was hung vertically in an electric furnace through which a stream of pure hydrogen was kept flowing continually. Having maintained the crucible above the melting point of the alloy for a minute or so, the crucible was raised out of the furnace and allowed to cool in the hydrogen stream for five minutes and then quenched in water. It was found that quite perfect castings were obtained by this procedure, having the form of cylinders roughly 3 mm diameter and 5 cm long. These castings were sealed in silica tubes in helium at atmospheric pressure, annealed 168 hours at 630°C in a small electric furnace, and finally quenched in water. This type of

[4] C. S. Smith, Physics **6**, 47 (1935).
[5] N. F. Mott and H. Jones, *Properties of Metals and Alloys* (Oxford University Press, 1936), p. 211.
[6] Bi has a rhombohedral lattice with two atoms in the unit cell. Cu_5Zn_8 has a complex cubic structure, containing 52 atoms in the unit cell. All the gamma-phases have this number of atoms in the unit cell, but the proportions of the components at the ideal composition is in accordance with Hume-Rothery's rule, the valence electrons per atom being 21/13.

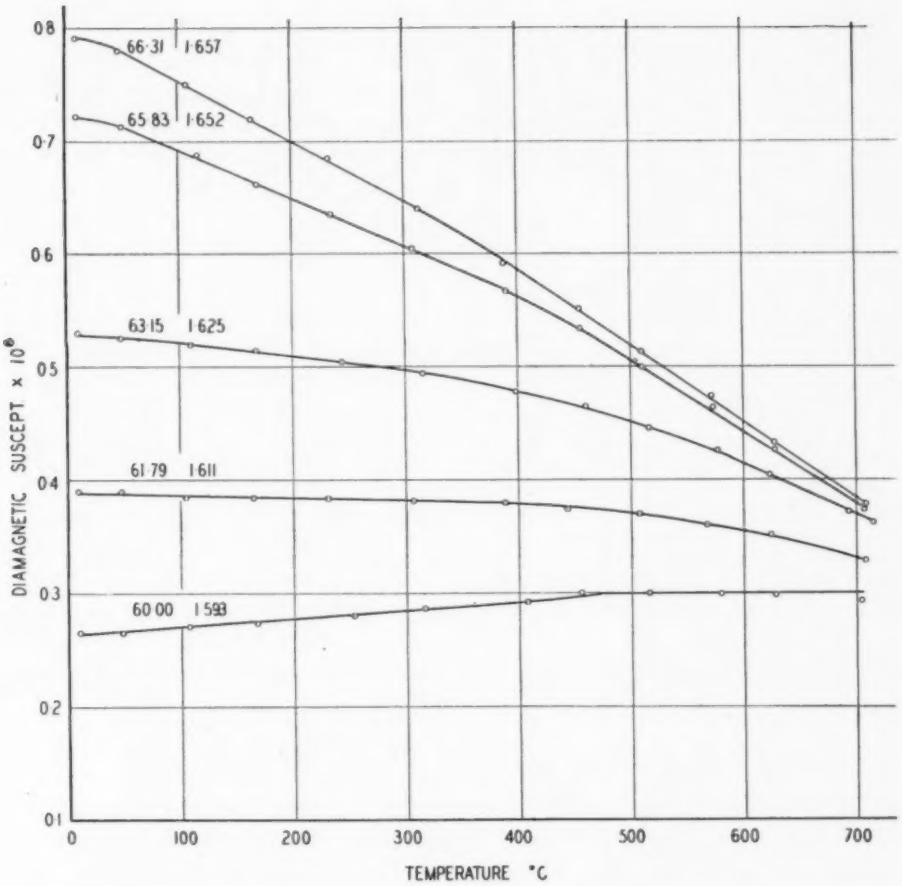

FIG. 2. Curves showing the relation between specific susceptibility and temperature for some gamma-brasses. The parameters are, first, zinc content by weight (in percent), followed by the electron ratio.

heat treatment was chosen in preference to a slow cooling from the high temperature since, as Smith showed, the selected process tended to retain any small iron impurity in solution and hence render it nonferromagnetic in the final measurements.

After annealing the specimens were removed from their silica tubes and cut in half. Due to the brittleness of the alloys, it is difficult to break them at a predetermined place. They tend to shatter into a number of small pieces, unsuitable for a magnetic measurement, if a hammer and chisel are used. To avoid such accidents a peripheral "nick" was ground with a thin emery wheel at the desired place. This was found to be very satisfactory, the metal always breaking cleanly at the nick when lightly bent between the fingers. One-half of the specimen was now resealed in a thin, close-fitting silica tube in a helium atmosphere at atmospheric pressure. The other half was used for chemical analysis.

The analysis was by the usual electrolytic method, using Pt electrodes and rotating anode. An $HNO_3-H_2SO_4$ solution was employed. The residual solution, after the Cu had plated out, was always tested for remaining Cu. This was done by bubbling H_2S through the solution, filtering through quantitative paper, and burning in air to an ash. The copper could then be estimated from the weighed CuO content of the crucible. Actually the residual Cu was always found to be negligibly small when the time taken for the electrolysis was about 3.5 hours. The Zn was of course calculated by difference. The analyses are probably correct to better than 0.2 percent.

The magnetic measurements were carried out

on a Weiss-Foëx translation balance, using a very large water-cooled Weiss electromagnet. The measurements were all made in terms of a very pure gold standard of the same dimensions as the specimens, whose mass susceptibility is known to be $\chi=(0.145\pm.001)\times10^{-6}$. Temperatures were measured with a chromel-alumel thermocouple, the high temperatures being produced by a furnace of the same type as described by Foëx and Forrer.[7] In order to check the accuracy of the temperature measurements two runs of susceptibility *vs.* temperature were made on samples of very pure Bi and Sb. These two metals show a *sudden*, large decrease in susceptibility on melting which is very easy to observe. From the susceptibility temperature curve, therefore, the melting point can be obtained and compared with the known values. The magnetic results gave, for the melting points of Bi and Sb, 270°C and 629°C, respectively, in excellent agreement with the accepted values, and satisfactorily checking the thermocouple.

In order to test for the presence of free iron in the samples, the susceptibility was measured at a number of different field strengths at both room and higher temperatures. By plotting χ_{obs} *vs.* $1/H$ [8] one obtains a straight line, which is parallel to the $1/H$ axis if no free iron is present. This was found to be very closely the case for all samples. The range of field used was about 9000 gauss in these tests.

Results

Five alloys were prepared and their susceptibilities determined at room temperature. These results are plotted in Fig. 1 together with Smith's values for the same system. Considering the different source of the alloys in the two cases and the different technique used in measurement (Smith used the Gouy method) the agreement between the two sets of measurements is quite satisfactory. At low temperature the susceptibility increases linearly with electron ratio[9] over the gamma-phase. The significance of this result will be discussed later. As Smith has shown, this low temperature linearity holds for all gamma-phase alloys so far tested.

Figure 2 shows the observed variation of the specific susceptibility with temperature for the five alloys. It will be noted that for alloys of small electron ratio the temperature coefficient of susceptibility is positive whereas at the other end of the composition range this susceptibility is decidedly negative (as is the case for polycrystalline Bi and Sb). At a point near the theoretical composition Cu_5Zn_8 the susceptibility is nearly temperature independent.

Another curious feature about nearly all these alloys is to be seen in the vicinity of 400°C. The temperature coefficients above and below this temperature are seen to be quite different, the coefficients being, in general, more negative at the higher temperature. This cannot be attributed to any errors indigenous to the apparatus since some blank tests on pure SiO_2 specimens the same size as the alloys gave normal results over the whole temperature range.

Upon cooling the specimens down (fairly rapidly) to room temperature the susceptibility always returned to its initial value and the curve could again be retraced without hysteresis.

Another way of presenting the results is to plot susceptibility *versus* electron ratio for selected temperatures other than room temperature. Two such curves, taken from the data in Fig. 2, are plotted as broken lines in Fig. 1. The linearity found to hold at room temperature is seen to be exceptional rather than general.

Discussion

It has been mentioned previously that an electron gas obeying the Fermi statistics in a constant potential field gives rise to a small residual paramagnetism which is temperature independent and such a model is accordingly inadequate to explain the results recorded here. If, however, as Bloch showed, account is taken of the perturbing potential of the ions forming the lattice a quite different state of affairs exists. It turns out, in this case, that the occupied

[7] G. Foëx and R. Forrer, J. de physique **7**, 180 (1926).

[8] If free iron be present in the specimen it is clear that the observed susceptibility (χ_{obs}) will be given by $\chi_{obs}=\chi+\sigma/H$ wherein χ is the true "iron-free" susceptibility and σ is the specific intensity of magnetization of the iron impurity. Iron in combination with the γ(Cu-Zn) alloy has a susceptibility comparable to that of the pure alloy and its effect is therefore negligible when present in traces only.

[9] This is the ratio of valence electrons to atoms. In this alloy Cu has a valence of 1 and Zn a valence of 2.

energy surfaces plotted in momentum space are discontinuous across certain planes in this space, the orientation of these planes being determined by the crystalline symmetry of the metal, their position by atomic and crystallographic constants. Such a surface of constant energy at the highest occupied level is called the "surface of the Fermi distribution"; they are sharply defined at low temperatures and represent the boundary between energy states which are occupied and states which are unoccupied. The geometrical figure defined by adjacent surfaces across which the energy is discontinuous and between which permitted states lie forms a "Brillouin zone." If the number of "free" electrons per atom is less than the possible number of states in the lowest zone we have an insulator. For many metals there are more than sufficient electrons to fill the lowest Brillouin zone and accordingly an overlapping of electrons into the next higher zone takes place. It further turns out that when the surface of the Fermi distribution lies just below the outer boundary of a zone, the metal in question is likely to have a large diamagnetism. This proves to be the case for bismuth and Jones calculates that at room temperature about 10^{-4} electrons per atom overlap into the next zone.

In the case of gamma-brass, the lowest zone contains 90 possible states and the electron ratio for the theoretical composition (Cu_5Zn_8) is 21/13 (=1.615) so that there are 84 electrons per unit cell of 52 atoms. This first zone is very symmetrical, the inscribed sphere containing 1.54 states per atom, and we may expect overlapping to occur when the electron ratio is greater than 1.54. Since the lowest electron ratio for the gamma-brass phase is about 1.58, it follows that the alloys in this phase should be highly diamagnetic and very similar in their properties to bismuth.

If, as the theory indicates, the overlapping electrons are responsible for the strongly diamagnetic character of both bismuth and the gamma-brasses, we should expect that any similar change in the number of overlapping electrons would be likely to produce comparable effects in the magnetic properties of these elements and, in point of fact, the available experimental evidence supports this view. By investigating the thermomagnetic properties of a series of alloys across the gamma-phase we have, in effect, investigated a series of similar metals differing from one another by the number of their overlapping electrons. We are in a position, so to speak, to artificially control the overlap responsible for diamagnetism. A similar process may be carried out for bismuth by alloying it with minute amounts of another element possessing a valency greater or less than the base metal.

Thermomagnetic measurements on bismuth alloyed with small amounts of lead have been reported by Schoenberg and Uddin.[10] Addition of Pb (valence 4) to pure Bi (valence 5) will decrease the number of overlapping electrons, and should, on the above argument, produce a series of metals whose thermomagnetic behavior is similar to the gamma-brasses as copper content increases. Comparison of the curves in Fig. 2 with those given by Schoenberg and Uddin[11] shows this to be the case. A Bi-Pb alloy containing 4 percent Pb shows a positive temperature coefficient as does our 60 percent brass alloy. In both cases the overlap is small. The pure Bi however shows a negative coefficient as does our 66.31 percent brass and here the overlap is great. Apart from this experimental comparison, no very detailed comparison with theory can at present be given, since the temperature variation of diamagnetism has not as yet been worked out in detail. It is however likely to depend, in a first approximation, upon the same factors that are responsible for paramagnetism in some metals, such as the alkaline earths. This case has been worked out by Stoner[12] and he shows that the temperature dependence depends markedly on whether there is an overlapping of states or not, and that the temperature coefficient may be either positive or negative. It is probable therefore that the observed results for diamagnetics could be explained within the framework of the present theory.

In conclusion I should like to express my thanks to Dr. C. S. Smith of the American Brass Company for discussions I have had with him and also to Professor L. W. McKeehan for his interest and advice during this work.

[10] D. Schoenberg and Z. Uddin, Proc. Roy. Soc. **156**, 687 (1936).

[11] See Fig. 2, page 694, of this paper. (Reference 10.)

[12] E. Stoner, Sci. Rep. Tohoku Imp. Univ. (Honda Anniversary Volume), p. 283 (1936).

On Vibrations Produced During Machining on Lathes

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Indian Institute of Science, Bangalore, India
(Received June 18, 1937)

1. INTRODUCTION

ONE of the difficulties that is commonly met in securing a high degree of accuracy in precision lathe work is that vibrations are set up during machining because of surface irregularities. Until recently, these irregularities were believed to be in the form of peaks and valleys; but now it has been shown by the use of the profilograph designed by Willis G. Meyers[1] that they are of a decided bluntness, thus indicating the wave form of the surface. The cause of the vibrations giving rise to these irregularities is not fully understood and in many cases, the finishing of the surface is achieved by grinding, lapping and honing. Since a complete solution of this problem will be attained only by an understanding of the source of these vibrations, the present investigation on the vibrations of thin plates during surfacing on lathes was undertaken by the author.

2. METHOD AND RESULT

A metal plate which is provided with a small hub at its center is held centrally on the lathe. A short sharp cutter is clamped rigidly in the tool-rest as usual and by means of the automatic transverse feed, a light cut is taken from the plate. As the cutter moves from the center to the end it starts transverse vibrations in the plate. Once the plate begins to vibrate, the cutter traces crests and troughs in it. The accompanying plate, Fig. 1, shows the nature of the surface obtained. The angular velocity of the plate is clearly the same as that of the spindle. If n is the number of revolutions of the spindle per second and m is the number of crests or troughs for one revolution the frequency of vibration is clearly nm.

The various factors that are likely to contribute to the production of the irregularities on the plate are (1) the vibrations of the lathe as a whole, (2) the vibrations of the parts of the lathe such as the headstock, bed, toolrest, tool etc. and (3) the vibrations of the plate itself in the process of turning. The method of investigation as to which of the above factors is responsible for the vibrations, consists of determining the vibration frequencies nm of plates of the same metal but having different thickness, at different radii and for varying speeds of the lathe spindle.

Table I gives the number of crests in each of six equal segments along circles of different radii of a brass plate. The results show that the vibrations are steady and uniform and are therefore, due to a periodic vibration in the system. The higher harmonics of the plate also get more

TABLE I.

Radius in cm	Segments 1	2	3	4	5	6	Total No. of Crests
5.0	39	39	38	39	39	39	233
6.1	39	39	39	40	38	39	234
6.8	39	40	40	38	39	39	235
7.9	39	39	shows harmonics				

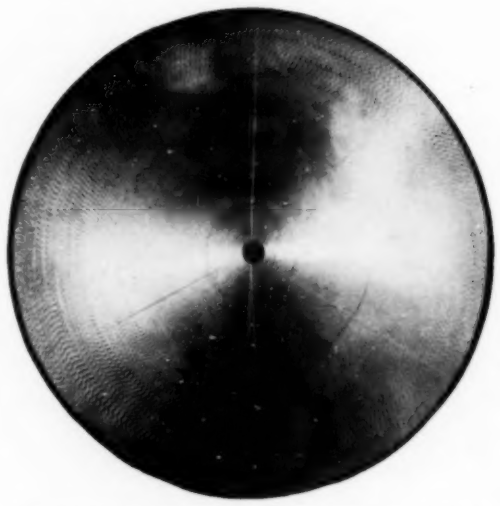

FIG. 1. Appearance of chatter vibrations occurring during machining on lathes.

[1] Willis G. Meyers, Machinist, March 7, 1936, 96 E.

and more prominent as the radius becomes large.

Table II gives the frequencies of a brass plate

TABLE II.

SPEED OF SPINDLE r.p.m.	RADIUS OF CIRCLE FOR THE CRESTS	NO. OF CRESTS IN ONE REVOLUTION	FREQUENCY PER SEC.
301	4 cm	88	441
200	(1) 5 cm	(1) 132	(1) 442
	(2) 6 cm	(2) 86	(2) 288
135	8 cm	128	288

of thickness 0.33 cm and radius 9 cm at different spindle speeds. To avoid as far as possible the small change in thickness occurring with each cut, the speed of rotation is changed during the same cut. Hence the crests for different speeds are traced out at different radii of the plate. It may be observed that a change of frequency occurs at greater diameters. This is caused by the fact that the plate emits two notes which have also been revealed by the optical method given below. The higher frequency is preferentially excited when the diameter is small and the lower frequency when the diameter is large. The constancy of these frequencies, however, shows that the vibrations are not caused by the tool or the bed of the lathe.

Table III gives the frequencies p' of four

TABLE III.

PLATE	$2h$ IN CM	a IN CM	NO. OF CRESTS	SPEED PER SEC.	FREQ. p' sec.$^{-1}$	FREQ. p sec.$^{-1}$	p'/p	$\frac{a^2p'}{h}$
								$\times 10^5$
1	0.59	8.6	234	2.28	534		—	1.34
2	0.265	5.075	203	3.67	677	1091	0.6	1.32
3	0.156	7.37	48	3.67	176	280	0.6	1.22
4	0.33	9.0	132	3.67	442	450	1.0	2.22
			86	3.67	288		0.6	1.40

brass plates of different thickness as determined by the above method. The frequencies p of their free vibrations are also determined optically. In the optical method a narrow beam of light is reflected from a small strip of mirror attached to the surface of the plate. The plate is vibrated by a gentle blow at different diameters and the reflected pencil of light is incident on a falling photographic plate. The frequencies are calculated by comparison with the curve of a standard tuning fork obtained on the same plate. From the table it may be seen that the ratio p'/p is very nearly constant showing thereby that the degree of forcing depends on the frequency of the plate. The discrepancy in the case of the higher frequency of plate 4 is evidently due to the fact that this frequency corresponds to a mode of vibration which is different from that of the other plates.

In the theory of the vibration of plates of given lateral dimensions, the frequency p of any particular normal mode of vibration is given by $p^2=(4/3)(E'/d)h^2m^4$ where h=semi-thickness, d=volume density, $E'=E/1-\sigma$, where E is Young's modulus and σ=Poisson's ratio and m is a constant. Poisson has shown that m varies directly as $1/a$, where $a/2$ is the radius of the plate. Hence it follows that $p \propto h/a^2$ or a^2p/h is constant for the normal mode of vibration. From the tables it is seen that a^2p'/h is constant for the normal vibration of all the plates. This establishes that the vibrations are entirely due to the plates themselves. A smooth nonwavy surface could thus be obtained if the plate is rendered rigid and vibrationless by additional supports.

The above work was carried out by the author some years ago in the Physical Laboratories of the Presidency College, Madras and the author's thanks are due to Dr. H. Parameswaran for suggesting the problem and to the University of Madras for the grant of a stipend which made this work possible.

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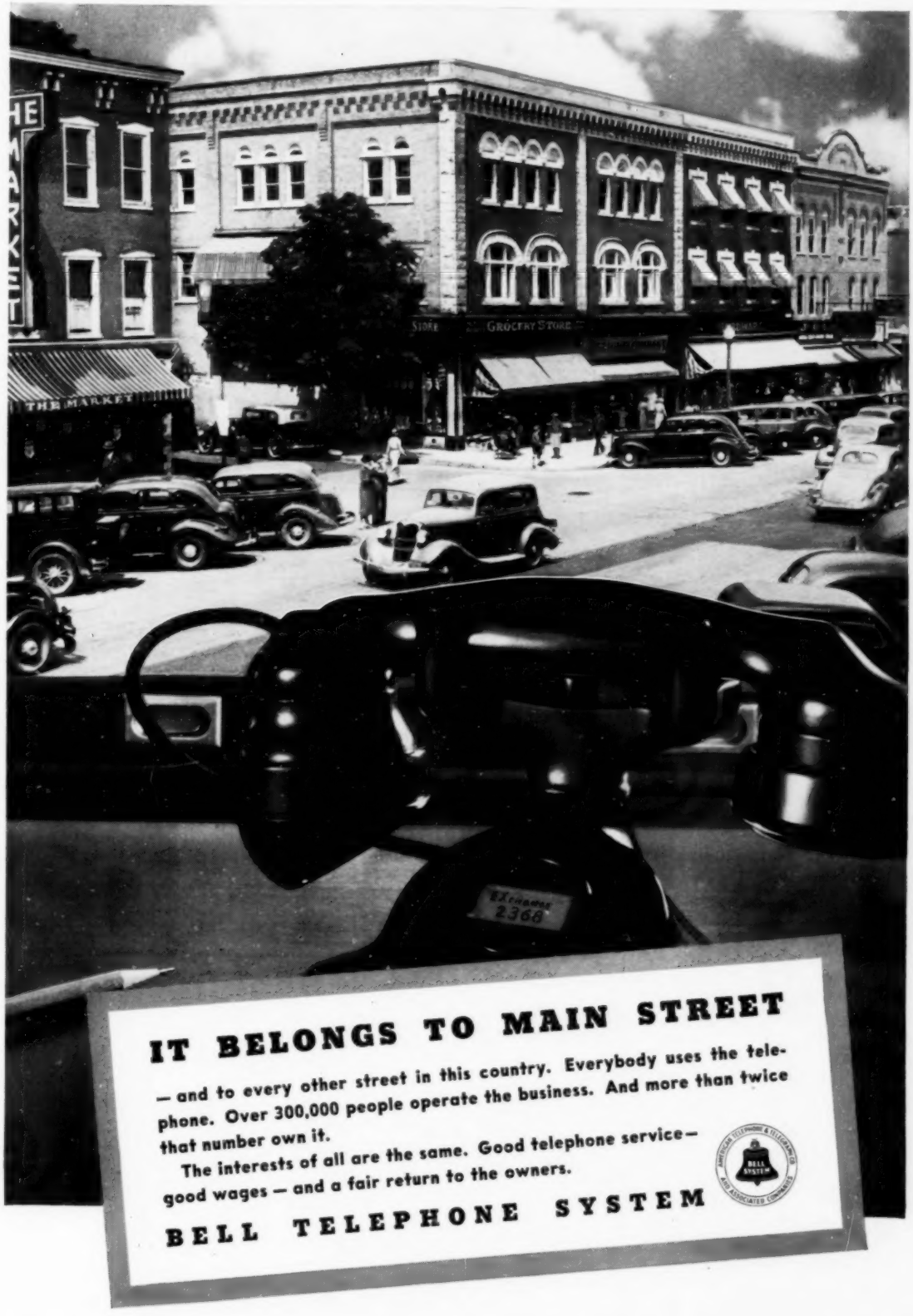

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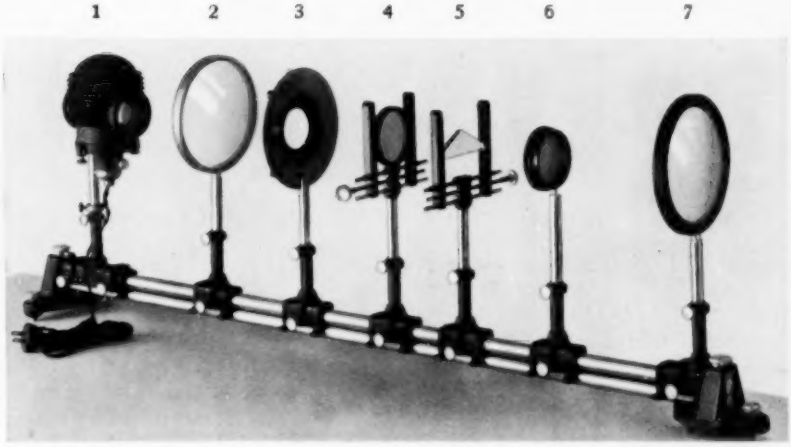

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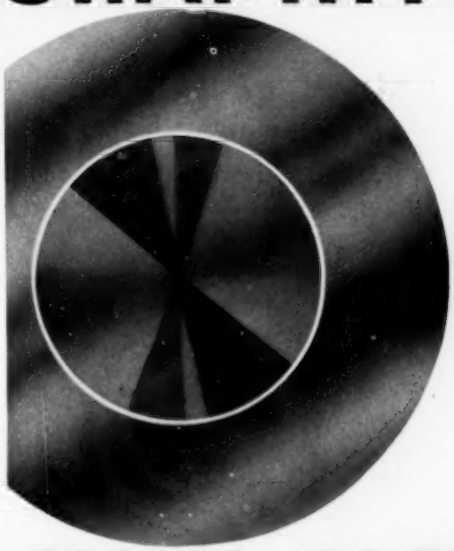

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